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COMPARATIVE MEASUREMENTS OF TOTAL TEMPERATURE IN A SUPERSONIC TURBULENT BOUNDARY LAYER USING A CONICAL EQUILIBRIUM AND COMBINED TEMPERATURE-PRESSURE PROBE

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COMPARATIVE MEASUREMENTS OF TOTAL TEMPERATURE IN A SUPERSONIC TURBULENT BOUNDARY LAYER USING A CONICAL EQUILIBRIUM AND COMBINED TEMPERATURE-PRESSURE PROBE

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July 1974

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The predominant probes used for measuring total temperature in a compressible boundary-layer flow are described. The results of a direct comparison between two of these probes, the conical equilibrium temperature probe (Danberg probe) and the combined temperature-pressure probe of the DFVLR-AVA, are presented. The comparison was made by testing the probes simultaneously

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in the nozzle-wall turbulent boundary-layer flow of the NOL Boundary Layer Channel at zero and moderate heat-transfer conditions. The measurements were made at a free-stream Mach number of 4.9 and a Reynolds number per meter range between 1.84×10^6 and 2.57×10^7 at two axial locations in the uniform flow regime of the nozzle. The results of the comparison showed a good agreement between the two probes, with a maximum difference in total temperature measurement of less than ±2 percent over the range of application.

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COMPARATIVE MEASUREMENT OF TOTAL TEMPERATURE IN A SUPERSONIC TURBULENT BOUNDARY LAYER USING A CONICAL EQUILIBRIUM AND COMBINED PRESSURE-TEMPERATURE PROBE

This report documents results obtained in a comparative experimental investigation of two probes used for the measurement of total temperature in the supersonic turbulent boundary layer.

This work was performed under the sponsorship of the Naval Air Systems Command, Task No. A32320/292/69R009-02-030 with Mr. W. C. Volz as project monitor. The work was carried out under the framework of the Data Exchange Agreement, "Boundary Layer Effects," between the United States of America and the Federal Republic of Germany (AF-68-G-7416). The authors wish to thank Messrs. F. W. Brown and F. C. Kemerer for their efficient operation of the facility and preparation of instrumentation.

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INTRODUCTION

Whereas the Mach number distribution in supersonic boundary layers can be obtained with sufficient accuracy from conventional Pitot probe measurements, the experimental determination of the total temperature requires a considerable effort in order to achieve high accuracy. Such reliable measurements are necessary to properly define the flow field in supersonic turbulent boundary layers.

The purpose of this paper is to report on the results of a direct comparison of two total-temperature measuring techniques. This is prefaced in the first part of the paper by a critical survey of existing total-temperature measuring instrumentation including the bare wire thermocouple probe, shielded stagnation temperature probe, mass flow probe, equilibrium temperature probe and combined temperature-pressure probe. The main advantages and disadvantages of these probes and their special application will be discussed. The second part of the paper describes the comparative probe measurements between the equilibrium temperature probe and the combined temperature-pressure probe.

SURVEY OF EXISTING MEASURING TECHNIQUES

Measurement Considerations

Conventional instruments for the probing of boundary-layer flows have been developed to measure either the total pressure, static pressure, total temperature or mass flow. In general, and for the range of application where perfect gas assumptions are valid, measurement of any three of the above four quantities

is sufficient to fully define a local flow field. These quantities are measured either directly as in the measurement of the total pressure behind a normal shock wave with a Pitot probe, or indirectly as in the use of probes which measure a local surface property which relates to one of the above quantities through the use of basic perfect gas flow relations. An example of the latter is the conical equilibrium temperature probe which is used to infer the local stagnation temperature from the measured cone recovery temperature and Mach number.

In nearly all cases the total-temperature evaluation is dependent upon the local Mach number. The Mach number is generally obtained from the total pressure which is measured with a Pitot probe. It is widely accepted that the accuracy of the Pitot probe measurements are affected by three factors: 1. the distortion of the local flow streamlines about the probe in the vicinity of the wall, 2. displacement effects due to the integration of a nonuniform pressure distribution over the probe open area which implies the center of pressure is different from the probe geometric center, and 3. viscous effects on the probe. These influencing factors on the Mach number evaluation are present in almost all experimental measurements and should be considered in the final analysis. These factors have been extensively studied for Pitot probes (Refs. 1 to 4).

Intuitively, the same factors should also apply to other probing devices. However, in the use of temperature probes the influences of these factors have not been reported in as much detail as with Pitot probes. The reasons are that viscous effects are generally included in the probe calibrations and, for most applications, temperature gradients in the

boundary-layer flow field are not as severe as the pressure gradients and do not warrant a displacement correction.

Presently there are four basic probe designs in use to measure the total temperature. These are the bare wire thermocouple probe, the shielded thermocouple probe, the conical-equilibrium temperature probe and the combined temperature-pressure probe. Each probe has its special design features and operational limitations.

Bare Wire Thermocouple Probe

The bare wire thermocouple probe generally refers to the configuration shown in Figure 1 taken from Reference 5. The probe configuration developed by Yanta is essentially a cylindrical wire aligned with its axis normal to the flow streamlines. This sensing wire is made of two small thermocouple wires welded together to form a thermocouple junction at the center. Consequently, the instrument senses the wire temperature at its center. The stagnation temperature is deduced from a heat-balance equation and empirical expressions for convective heat transfer to a cylinder in cross flow as derived in Reference 6. These computations include corrections for Mach number and viscous effects and wire support conduction losses. The application of bare wire probes to hypersonic flow further necessitates corrections for radiation. I. Beckwith et al. in Reference 4 and I. E. Vas in Reference 7 both considered heat losses due to radiation in addition to the conduction losses.

Due to the small dimensions of the bare wire probe, its application is ideally suited to boundary-layer investigations because measurements can be made very close to the wall. Because of the small mass of the wire, the probe also has a relatively fast response time in comparison to the other probes discussed herein.

The limitation of this probe relates to the aerodynamic loading of the wire at high Reynolds numbers. Early probe designs required large ratios of wire length to diameter to minimize conduction losses. A wire length to diameter ratio between 100 and 200 was generally used. This large ratio, together with the small wire diameter, usually resulted in a wire breakage due to high aerodynamic loading. Consequently, the probe was used only in relatively low dynamic-pressure flows. This large length-to-diameter ratio is no longer a stringent requirement in probe designs where wire support temperatures are monitored to provide an accurate correction for the end losses (See References 5 and 8). As an alternate means of overcoming the difficulties at the high dynamic pressures, H. D. Harris, Reference 9, used an arrangement proposed by W. S. Bradfield et al., Reference 10. In this arrangement, the thermocouple wires are mounted on the thin leading edge of a wedge-shaped probe-tip made of a heat-insulating material.

Shielded Stagnation Temperature Probe

The basic design of a shielded stagnation temperature probe is shown in Figure 2 as developed by E. M. Winkler, Reference 11, in 1954. The main advantages of this probe are that the thermocouple wire is protected by a shield against high dynamic pressure loads, and that the thermocouple is surrounded by subsonic flow. The subsonic flow in the probe is maintained by venting the air through a hole at the base of the probe where the probe entrance area is much larger than the vent-hole area. A sonic condition exists at the vent-holes on the condition that the ratio of Pitot to static pressure is over-critical. With a fixed vent-hole opening the mass flow inside of the probe varies with the free-stream Reynolds

number. This implies a change of the convective heat transfer to the thermocouple junction and thus a change in the probe recovery factor. For this reason, the probe must be calibrated over the range of flow conditions to be investigated.

Further improvements of shielded thermocouple probes have been made by many experimenters since the early work of E. Winkler. R. E. Larson and A. R. Hansen, Reference 12, reduced the size of such probes and P. J. Bontrager, Reference 13, used a vented double shield to minimize radiation losses at elevated temperatures.

Mass Flow Probe

Since the total temperature can be evaluated from the measurements of static pressure, total pressure, and mass flow, an indirect measurement of total temperature can be made if a means is found of evaluating these quantities, in particular, the mass flow. In 1953, D. Coles, Reference 1, proposed a technique to measure the mass flow. If the flow is supersonic, one may visualize a sharp-edged, tubular probe with a sufficiently low internal pressure to permit the existence of an attached shock system at the entrance (See Figure 3). The probe inlet area then defines the cross section area of the stream tube entrained by the probe. D. Coles offered two methods to measure the mass-flow rate. In the first method the probe is discharged into an evacuated receiver for a measured time interval. The mass-flow rate is calculated from the initial and final pressures and temperatures in the receiver. This method was used successfully by L. L. Liccini, Reference 14, in a hypersonic boundary-layer flow. The major conclusions from Reference 14 were that the mass flow probe error increased as Reynolds number was decreased and that a circular probe was more satisfactory than a rectangular probe of the same height.

Figure 3 shows the second method of evaluating the mass flow as applied by R. J. Stalker (Ref. 15). In this case a calibrated sonic metering orifice, with a diameter larger than the probe opening, is used between the probe and a vacuum pump. Boundary layer measurements using the Stalker mass flow probe were carried out by G. Hovstadius (Ref. 16). Practical difficulties encountered with the application of this probe appeared in the limited accuracy of the calibration procedure used to get the effective probe entrance and the sonic nozzle diameters.

In using a mass flow probe, the total temperature is inferred from the two quantities: mass flux, ρu, and the Mach number, M. Both quantities can be obtained from the same mass flow probe. The mass flux can be determined from the mass-flow rate measured and an effective probe entrance area. The Mach number can be determined by disconnecting the vacuum system from the probe and essentially using the probe as an impact pressure indicator. This, together with a measured static pressure, permits the calculation of the Mach number from the Pitot-Raleigh formula.

The primary condition for the probe to operate successfully is that the flow must enter the probe undisturbed, i.e., the stream tube captured by the probe must have the same cross-sectional area as the probe entrance. In supersonic flow this condition can be attained with a sharp leading-edge probe where the oblique shock wave is attached to the leading edge. In subsonic flow it is difficult to define the size of the stream tube captured by the probe.

Combined Temperature-Pressure Probe

The combined temperature-pressure probe, see Figure 4, is essentially a modified version of the shielded thermocouple probe where the sonic vent-holes of the shielded thermocouple probe are replaced by a mass-flow metering system. The modification was based on the calibrations of shielded thermocouple probes

where it could be concluded that the dependency of the probe recovery factor on Reynolds number could be related to the mass flow through the probe. A detailed description of such a probe, its calibration, and application for boundary layer measurements is given in Reference 17.

In order to measure the mass flow through the probe, a metering system is used whereby orifices of known area are inserted between the probe and a vacuum pump. The mass flow, and therewith the convective heat transfer to the thermocouple, is controlled by the size of the metering orifice. The orifice size is selected such that a sonic velocity is assured at the orifice and the mass flow through the probe can be determined from the orifice open area and the pressure and temperature ahead of the orifice.

One limitation of this probe results from the relatively long response time required to reach equilibrium conditions when exhausting the probe through small orifices at low probe pressures. Furthermore, in this low probe-pressure range where the Reynolds number is correspondingly low, the relative heat conduction through the probe thermocouple leads can become large in relation to the low convective heat transfer to the thermocouple and a calibration has to be established for low mass flow rates. One advantage of the probe is that it is particularly adaptable to measurements in complex flow fields because both the Pitot pressure and stagnation temperature can be measured consecutively at the same spacial location.

Conical Equilibrium Temperature Probe

The conical equilibrium temperature probe as developed by J. E. Danberg, Reference 18, consists of a sharp, small angled cone of low emissitivity, high conductivity metal supported by a thermal insulator (See Figure 5). The cone temperature, measured with a thermocouple imbedded in the base of the cone, is assumed to be the recovery temperature

of the cone. Comprehensive calibration measurements endorse a cone recovery factor calculation based on a laminar boundary layer flow assumption, i.e., $r_p = (Pr)^{1/2}$ when radiation losses are negligible. Based on this assumption, the total temperature evaluation is reduced to a minimum since only the cone temperature and Mach number need be evaluated.

The limitations of this probe arise from the difficulties encountered in constructing probes of small diameter. For this reason the probes cannot measure as close to the surface in a boundary layer as, say, the bare wire probe. Because of the relatively large mass of the cone, temperature response is also relatively slow and such a probe is not suitable in a short duration flow facility.

Table 1 summarizes the applications and limitations of the various probes discussed. The chart should be useful in determining a particular probe's usefulness and application.

COMPARATIVE PROBE MEASUREMENTS

Test Program

It has been an acceptable practice to demonstrate the feasibility of a new probe design by comparing the results of the new design against the results from an established design in a well-defined flow field. Such was the case in the conical equilibrium temperature probe - shielded thermocouple probe comparison, Reference 18, and in the fine-wire stagnation temperature probe - conical equilibrium temperature probe comparison, Reference 5.

The present report shows the results of a comparison between the combined temperature-pressure probe and the conical equilibrium temperature probe. The comparison was made in

the Naval Ordnance Laboratory Boundary Layer Channel on the nozzle wall turbulent boundary layer flow at Mach number 4.9 for zero and moderate wall heat-transfer conditions.

Test Facility

The experiments were performed in the NOL Boundary Layer Channel, Reference 19, shown in Figure 6. The supersonic half-nozzle has for one wall a flat copper test plate, 2690 mm long, along which the boundary layer measurements were made. The opposite wall consists of an adjustable flexible plate which was contoured to produce a Mach 4.9 zero-pressure-gradient flow over the flat test plate beginning at 1397 mm downstream of the nozzle throat. The comparative boundary-layer stagnation temperature surveys were made at two locations along the test plate, corresponding to 1700 and 2060 mm downstream of the nozzle throat. The facility was operated at supply pressures of 1, 5, and 10 atmospheres and at a supply temperature of 340°K for the adiabatic wall runs and 420°K for the moderate heat-transfer runs. The wall temperature downstream of the nozzle throat region was held constant through the test runs by cooling the copper test plate with water. The test conditions are outlined in Table 2. Since the experimental arrangement and test procedures used in this study were similar to previous boundary-layer investigations in this facility, Reference 2 should be consulted for further information concerning the facility, test procedure, and boundary-layer characteristics.

Instrumentation

The boundary-layer profile surveys were made by simultaneously traversing the combined temperature-pressure probe and the conical equilibrium temperature probe through the boundary layer in a double-probe support configuration as shown in Figure 7. Each traverse was made from the free stream towards the plate with a maximum movement of 11 centimeters. Data were recorded with the probes at rest and only when the probe pressures and temperatures were observed to have reached equilibrium conditions. The local Pitot pressure was measured with the combined temperature-pressure probe. The local total temperature through the boundary layer was measured with both the combined temperature-pressure probe and the conical equilibrium temperature probe. Since the temperature probes were not of the same diameter nor mounted exactly at the same distance from the wall, the cone probe temperature data were interpolated to the location of the combined temperature-pressure probe. This allowed for the computation of all boundary-layer parameters at the same y location.

Data Reduction

The local Mach number was calculated from the measured Pitot pressure using the Rayleigh-Pitot formula or Bernoulli's equation depending on the Mach number range. The computations were based on the assumption of uniform static pressure through the boundary layer with the static pressure equal to the wall pressure.

The local stagnation temperature through the boundary layer was calculated from the following equation:

$$T_t = \frac{T_p}{r_p + \left(\frac{1 - r_p}{1 + \frac{\gamma-1}{2} M_p^2}\right)} \qquad (1)$$

where T_p is the measured probe thermocouple temperature, r_p is the probe recovery factor, and M_p is the probe reference Mach number. For the conical equilibrium temperature probe the recovery factor was equal to $Pr^{1/2}$ assuming laminar flow over the probe tip. The probe reference Mach number was assumed equal to the cone Mach number as determined from cone flow equations. For the combined temperature-pressure probe, the probe reference Mach number was equal to the local Mach number and the probe recovery factor was obtained from a calibration of r_p versus the mass flux through the probe. This calibration was obtained with the probe in the free stream for a limited range of probe mass flux conditions. The calibration is discussed in the next section. The local recovery factor of the combined temperature-pressure probe was computed for each location in the boundary layer from the measured mass flow rate at that location. Finally, the local static temperature, T, was obtained from the measured total temperature and Mach number using the isentropic relation

$$T = \frac{T_t}{1 + \frac{\gamma-1}{2} M^2} \qquad (2)$$

Combined Temperature-Pressure Probe Recovery Factor Calibration

Using the experimental arrangement shown in Figures 4 and 7, the calibration of the combined temperature-pressure probe was made with the probe located in the free-stream flow of the Boundary Layer Channel. The free-stream stagnation temperature was assumed equal to the tunnel supply temperature and a correlation of the probe temperature and stagnation temperature was evaluated in terms of the probe recovery factor, r_p, in the form:

$$r_p = \frac{T_p - T_\infty}{T_o - T_\infty} \tag{3}$$

where T_p is the measured probe temperature, T_o, the tunnel supply temperature, and T_∞, the freestream static temperature.

The mass flux through the probe was evaluated for each point in the calibration by exhausting the flow in the probe through sonic orifices. Because of this sonic condition at the orifice, the mass flux could be calculated from the measured pressure and temperature immediately ahead of the orifice, P_3 and T_3, and the effective diameter of the orifice, d_A, from the relation:

$$\dot{m} = \left(\frac{2}{\gamma-1}\right)^{\frac{1}{\gamma-1}} \left(\frac{\gamma}{\gamma+1}\right)^{.5} \frac{\pi}{4} d_A^{\,2} P_3 \left(\frac{2}{RT_3}\right)^{.5} \tag{4}$$

or, for $\gamma = 1.4$,

$$\dot{m} = 0.537\, d_A^{\,2} P_3 \left(\frac{1}{RT_3}\right)^{.5} \tag{5}$$

Recovery factor measurements were made for a range of mass flux conditions by passing the probe exhaust through orifices of differing diameter. A range of mass flow rates from 2×10^{-7} to 7×10^{-6} kg./sec. was attained by exhausting through orifices with geometric diameters of 0.155, 0.190, 0.246, 0.272, and 0.325 mm. Values of the geometric orifice diameter were used in this data reduction. In Reference 20, the effective nozzle diameters were evaluated and used in a similar date reduction procedure. This refinement had reduced the scatter in the calibration data.

The recovery factor calibration was obtained for a constant free-stream Mach number of 4.9 over a range of free-stream Reynolds number conditions. The tunnel supply pressure ranged from 1 to 10 atmospheres and the supply temperature was 340°K and 420°K. The results of the probe recovery factor calibration are shown in Figure 8, together with a least square polynomial curve fit of the data in the form

$$r_p = \sum_{i=1}^{5} a_i \left(e^{-\alpha \dot{m}}\right)^{(i-1)} \qquad (6)$$

Where: $\alpha = 0.32240 \times 10^6$

$a_1 = 0.981030$

$a_2 = 0.062327$

$a_3 = -0.185030$

$a_4 = 0.217070$

$a_5 = -0.186120$

Results of the Comparative Probe Measurements

The data described in the text of this report are documented in the tables of Appendix B. The nomenclature used in this computerized tabular output is defined in Appendix A.

Several considerations are worth commenting on at this time concerning the data documentation. First, the free-stream stagnation temperatures measured with the conical equilibrium and the combined temperature-pressure probe are seen to differ slightly for any particular test run. The main reason for this difference relates to the variation of the tunnel supply temperature between the time the two temperature measurements are made, i.e., the conical equilibrium probe temperature is measured at the time the Pitot pressure is measured while the combined temperature-pressure probe temperature is measured at a slightly later time when the probe is being vented. Because of possible variation in the tunnel supply temperature and the time lag between subsequent temperature probe measurements, the local stagnation temperature through the boundary layer was non-dimensionalized to the simultaneous free-stream stagnation temperature. All comparisons of temperature data are made in terms of the stagnation temperature ratio rather than the absolute temperature. It can be noted that for y distances of less than 0.75 mm, no temperature data are presented for the conical equilibrium temperature probe because of the larger probe size and its inability to measure as close to the wall as the combined temperature-pressure probe. And finally, it must be pointed out that no viscous flow or probe wall interference corrections are made to the Pitot pressure data. These

effects are present. However, their influence is restricted to low Reynolds number data and data very close to the wall. Because these regimes are associated with the low Mach number data for these tests the effect on the temperature evaluation is minimal as can be deduced from equation (1) as M approaches 0.

Comparisons of the measured stagnation temperature profiles obtained with the conical equilibrium temperature probe and the combined temperature-pressure probe are presented in Figures 9 to 12 for the two stations and two heat-transfer conditions. Agreement in stagnation temperature between the two probing techniques is good with a maximum deviation in stagnation temperature measurement of the order of 2 percent. The percent deviation in temperature measurement are shown in Figure 13 as a function of distance from the wall. The amount of data scatter in terms of temperature deviation appears to be equal between the data with and without heat transfer. However, the deviations appear to be greatest in the inner portion of the boundary layer where the Reynolds number is low. Under these conditions, the application of both probing techniques needs further qualification. It should be noted that the data reduction precedure used in Reference 20 led to smaller differences (±1 percent) between the two temperature measurements.

In proximity to the wall where the velocity and temperature gradients are the strongest, both probes exhibit averaging or displacement effects. Viscous interaction effects, as previously discussed, are predominant in this low Reynolds number regime. The conical equilibrium temperature probe data in the vicinity of the wall could be influenced by the interaction and possible reflection of the cone shock wave with the wall. The combined temperature-pressure

probe data need further examination because the exhausted mass flow rates through the probe were very low at the low Reynolds number conditions. Figure 14 shows the range of mass flow rates experienced in the boundary layer profiles presented in this report. It is observed that for the low Reynolds number tests (P_o = 1 atm.), the probe recovery factor had to be determined almost exclusively from the extrapolated portion of the curve fit. At these low probe mass flow rates, it is questionable whether the probe recovery factor is a function of the exhausted mass flux alone. By plotting the percent deviation in total temperature as a function of the exhausted mass flux through the combined temperature-pressure probe (See Figure 15), it can be seen that the percent deviation in total temperature measurement becomes larger with decreasing mass flux. It is still uncertain whether this trend is due to conduction losses on the temperature-pressure probe thermocouple or due to any one of the other previously mentioned effects on the cone probe temperature.

CONCLUSIONS

Probes used to measure stagnation temperature distributions in supersonic and hypersonic turbulent boundary layers are discussed. Limitations and applications of each probe are indicated.

Comparative probe measurements with the conical equilibrium temperature probe and the combined temperature-pressure probe lead to the following results:

The average differences between the measured stagnation temperatures in the Mach 5 supersonic turbulent boundary layers with and without heat transfer were in the range of ± 1.0 percent. At very low Reynolds numbers close to the surface the deviations increased to about 2 percent.

The conical equilibrium temperature probe is distinguished by its simple calibration, where the recovery factor can be assumed constant ($r_p = (Pr)^{1/2}$). Due to the relatively large probe size, measurements could not be obtained very close to the wall.

The combined temperature-pressure probe enables one to measure at one position of the probe the local stagnation temperature and total pressure. This can be important if complex flow fields are to be studied. Due to its smaller diameter, measurements closer to the surface could be made.

Although these investigations yielded a good agreement, further work should be undertaken to better classify and define the apparent discrepancies at low Reynolds numbers and in the vicinity very close to the wall.

REFERENCES

1. Coles, D., "Measurement in the Boundary Layer on a Smooth Flat Plate in Supersonic Flow," Part II, JPL Report No. 20-70, June 1953

2. Voisinet, R. L. P., Lee, R. E., "Measurements of a Mach 4.9 Zero-Pressure-Gradient Turbulent Boundary Layer with Heat Transfer, Part 1 - Data Compilation," NOLTR 72-232, 1972

3. Allen, J. M., "Pitot-Probe Displacement in a Supersonic Turbulent Boundary Layer," NASA TN D6759, April 1973

4. Beckwith, I. E., William, D. H., and Clark, F. L., "Comparisons of Turbulent Boundary-Layer Measurements at Mach Number 19.5 with Theory and an Assessment of Probe Errors," NASA TN D6192, June 1971

5. Yanta, W. J., "A Fine-Wire Stagnation Temperature Probe," NOLTR 70-81, 1970

6. Scrandon, M. D., Warshawsky, I., "Experimental Determination of Time Constants and Nusselt Numbers for Bare-Wire Thermocouples in High-Velocity Air Streams and Analytic Approximation of Conduction and Radiation Errors," NACA TN 2599, January 1952

7. Vas, I. E., "Flowfield Measurements Using a Total Temperature Probe at Hypersonic Speeds," AIAA Journal, Vol. 10, No. 3, pp. 317-323, March 1972

8. Behrens, W., "Total Temperature Thermocouple Probe Based on Recovery Temperature of Circular Cylinders," Int. J. Heat Mass Transfer, Vol. 14, pp. 1621-1630, 1971

9. Harris, H. D., "An Investigation of Turbulent Boundary Layer Characteristics with Particular Reference to the Effect of Heat Transfer and Pressure Gradient," Ph.D. Thesis, London University, 1970

10. Bradfield, W. S., Hanson, A. R., Sheppard, J. J., "Design, Calibration and Application of a Miniature Total-Temperature Probe," Trans. ASME, Ser. C., J. Heat Transfer, pp. 462-463, 1964

11. Winkler, E. M. "Stagnation Temperature Probes for Use at High Supersonic Speeds and Elevated Temperatures," NAVORD Report 3834, October 1954

12. Larson, R. E., Hanson, A. R., "Study of Subminiature Total Temperature Probes," NASA Report 2980, 1966

13. Bontrager, R. J., "Development of Thermocouple-Type Total Temperature Probes in the Hypersonic Flow Regime,"AEDC-TR-69-25, 1969

14. Liccini, L. L., "NOL Hypersonic Tunnel No. 4 Results VII: Development and Calibration of Mass Flow Probes in Hypersonic Flow," NAVORD Report 4078, November 1955

15. Stalker, R. J., "The Use of Mass Flow Probe for Measurement of Hypersonic Boundary Layer Properties," FFA Report AU-624, Part 1, 1970

16. Hovstadius, G., "Measurement of Boundary Layer Properties in Two Hypersonic Nozzles," FFA Report AU-624, Part 2, 1971

17. Meier, H. U., "A Combined Temperature and Pressure Probe for Compressible Flow," AIAA Journal, Vol. 7, No. 3, pp. 529-530, 1969

18. Danberg, J. E., "The Equilibrium Temperature Probe, A Device for Measuring Temperatures in Hypersonic Boundary Layers," NOLTR 61-2, December 1961

19. Lee, R. E., Yanta, W. J., and Carner, J. W., "The NOL Boundary Layer Channel," NOLTR 66-185, November 1966

20. Meier, H. U., Lee, R. E., and Voisinet, R. L. P., "Total Temperature Probes for the Investigation of Turbulent Boundary Layers at Supersonic Speeds," 5th International Congress on Instrumentation in Aerospace Simulation Facilities, ICIASF 73 Record, IEEE Publication No. 73 CHO 784-9 AED, 1973

LIST OF SYMBOLS

d_A	sonic metering orifice diameter
d_E	probe entrance diameter
$\dot{m}$	mass flux through probe
M	Mach number
M_p	probe reference Mach number
P	pressure
Pr	Prandtl number (for air, 0.72)
P_s	static pressure
P_{t2}	Pitot pressure
r	boundary layer recovery factor
r_p	probe recovery factor, $\frac{T_p - T}{T_t - T}$
R	gas constant
Re	Reynolds number per meter, $\frac{\rho_\infty u_\infty}{\mu_\infty}$
T	temperature
u	velocity
x	streamwise distance from nozzle throat
y	distance normal to test plate surface

Subscripts

aw	adiabatic-wall conditions
o	tunnel supply conditions
p	probe conditions
t	stagnation conditions

Subscripts (Cont.)

w	wall conditions
3	conditions immediately ahead of sonic metering orifice
∞	free-stream conditions

Abbreviations

CE	conical equilibrium probe
CTP	combined temperature-pressure probe

TABLE 1 - COMPARISON OF TOTAL TEMPERATURE PROBES

Probe Type	Fine Wire	Shielded	Mass Flow	Combined Temperature-Pressure	Conical Equilibrium
Measured Quantities	T_t	T_t	ρu, P_{t2}	T_t, P_{t2}	T_t
Ratings in Terms Of:					
Small probe size	G	F	F	F	(P)
Resistance to high dynamic loading	(F)	G	G	G	F
Response time	G	(P)	(P)	(P)	F
Ease of calibration	F	P	F	F	G
Low Reynolds number application	G	P	P	P	G
Application to subsonic flow	G	G	-	G	G
Application to hypersonic flow	G	G	-	-	G

G - Good
F - Fair
P - Poor
() - Improvement possible with further development
- - Unproved but possible

TABLE 2 - RUN NUMBERS AND TEST CONDITIONS

Run No.	Station (Meters)	p_o (Atms)	T_o (°K)	T_w/T_{aw}
108051	1.702	10.	340.	1.0
108052		5.		
108053		1.		
108104	2.057	5.		
108105		1.		
108091	1.702	10.	420.	0.8
108054		5.		
108055		1.		
108101	2.057	10.		
108102		5.		
108103		1.		

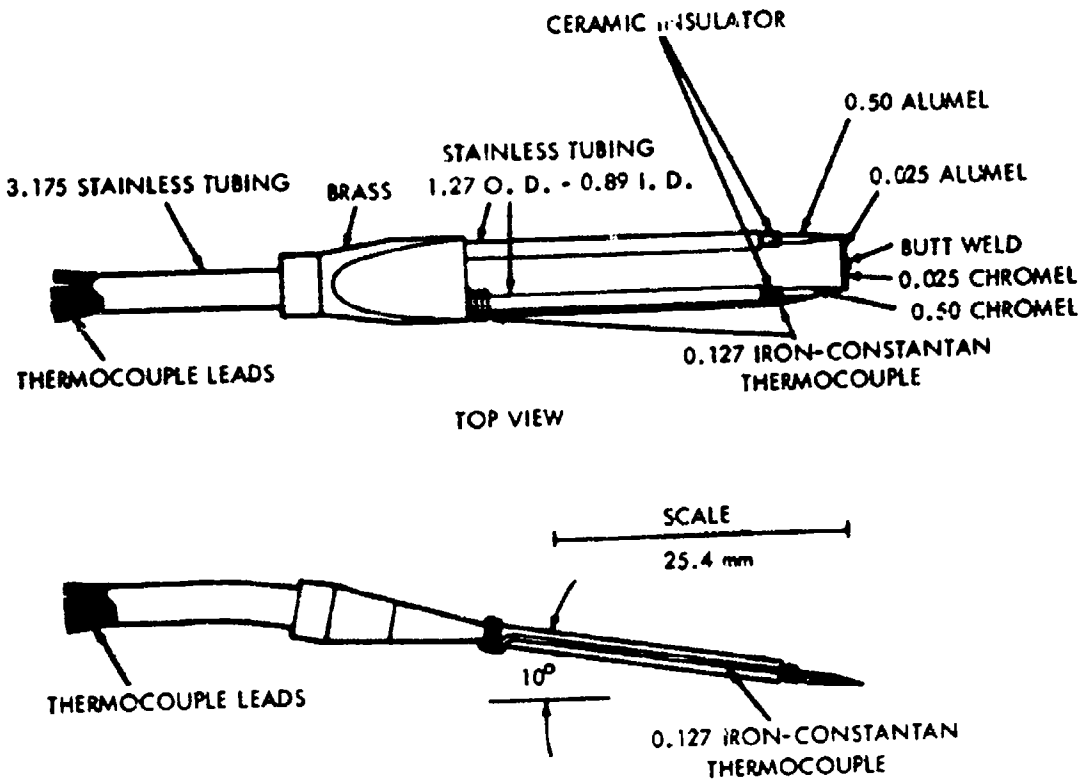

FIG. 1 SCHEMATIC OF FINE-WIRE PROBE (5)

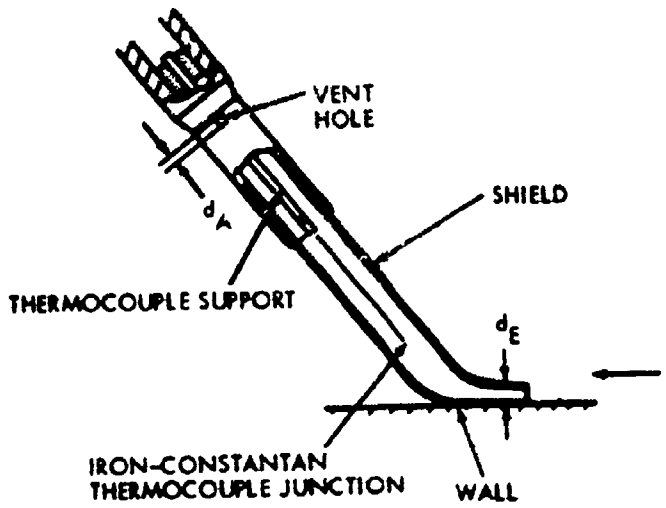

FIG. 2 SHIELDED THERMOCOUPLE PROBE (11)

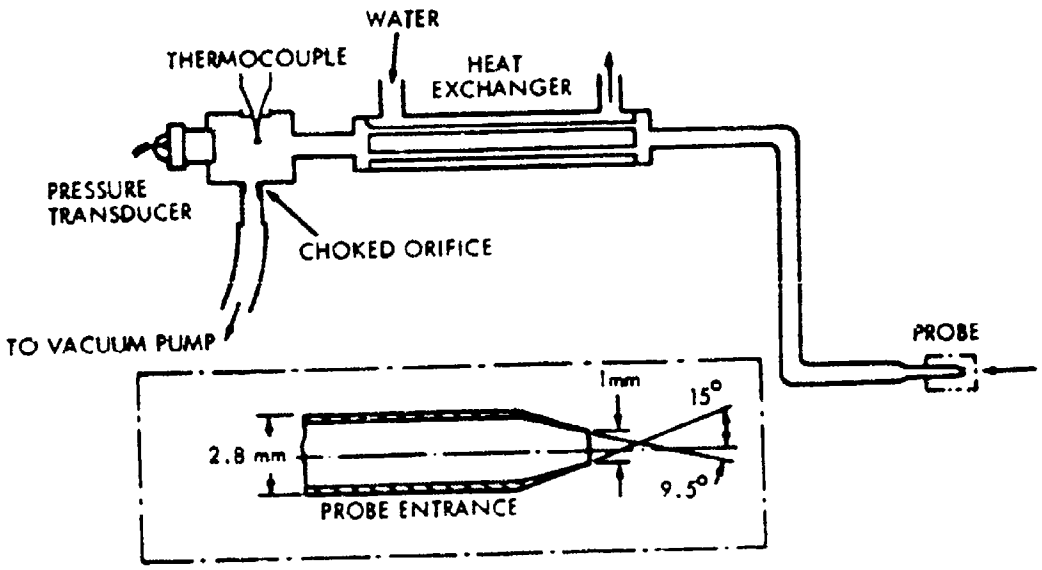

FIG. 3 MASS FLOW PROBE (15)

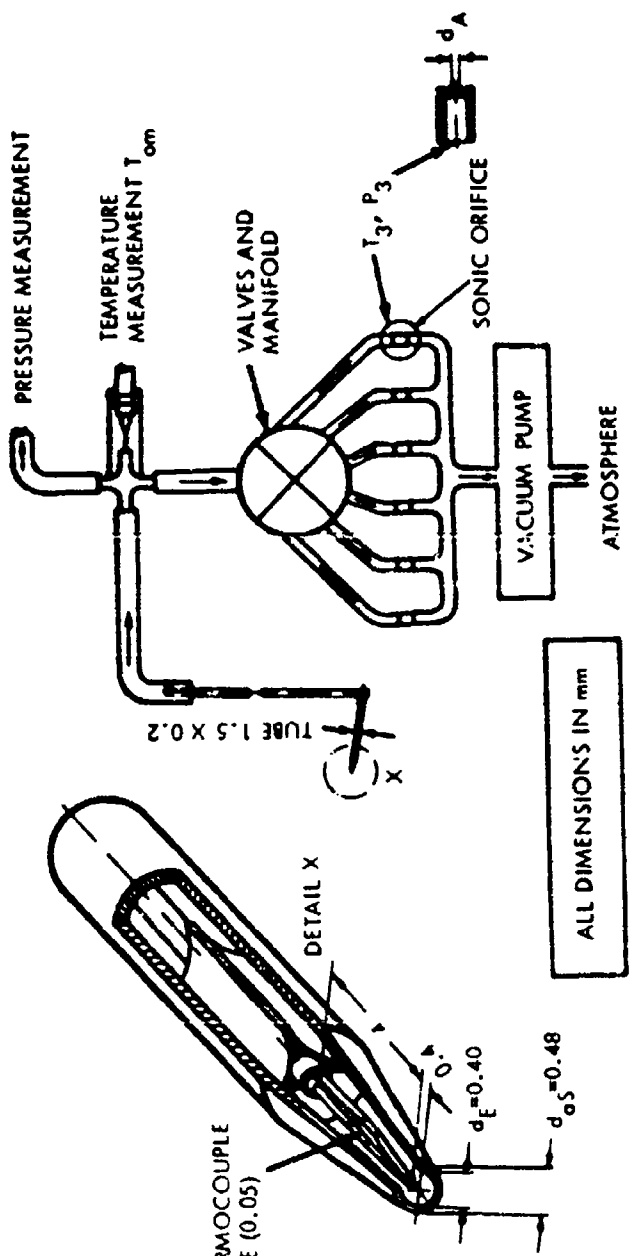

FIG. 4 COMBINED TEMPERATURE-PRESSURE PROBE (17)

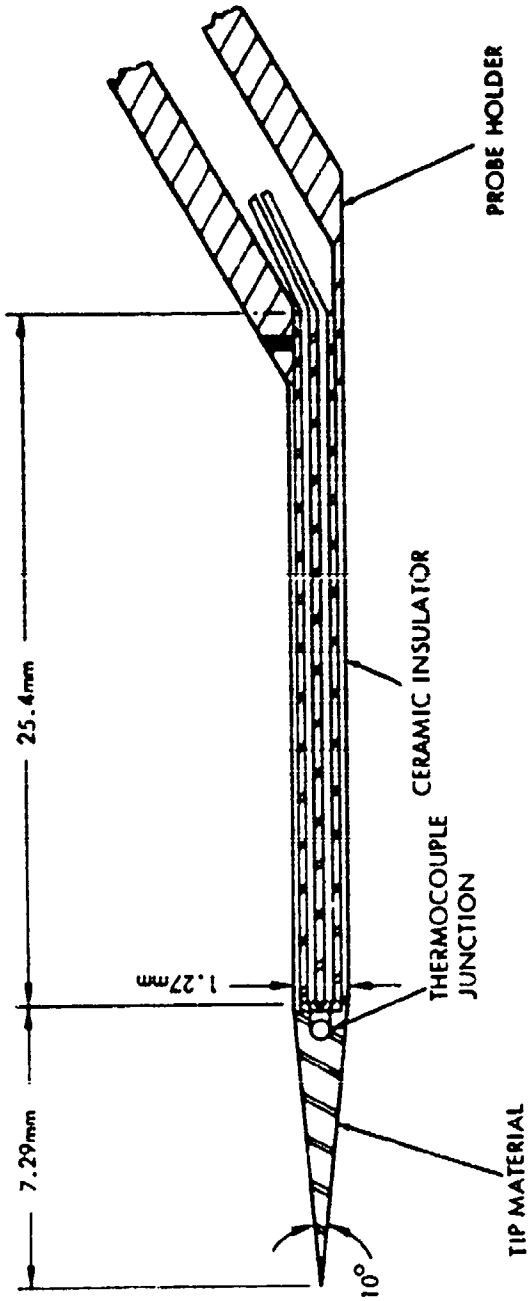

FIG. 5 DANBERG CONICAL EQUILIBRIUM TEMPERATURE PROBE (18)

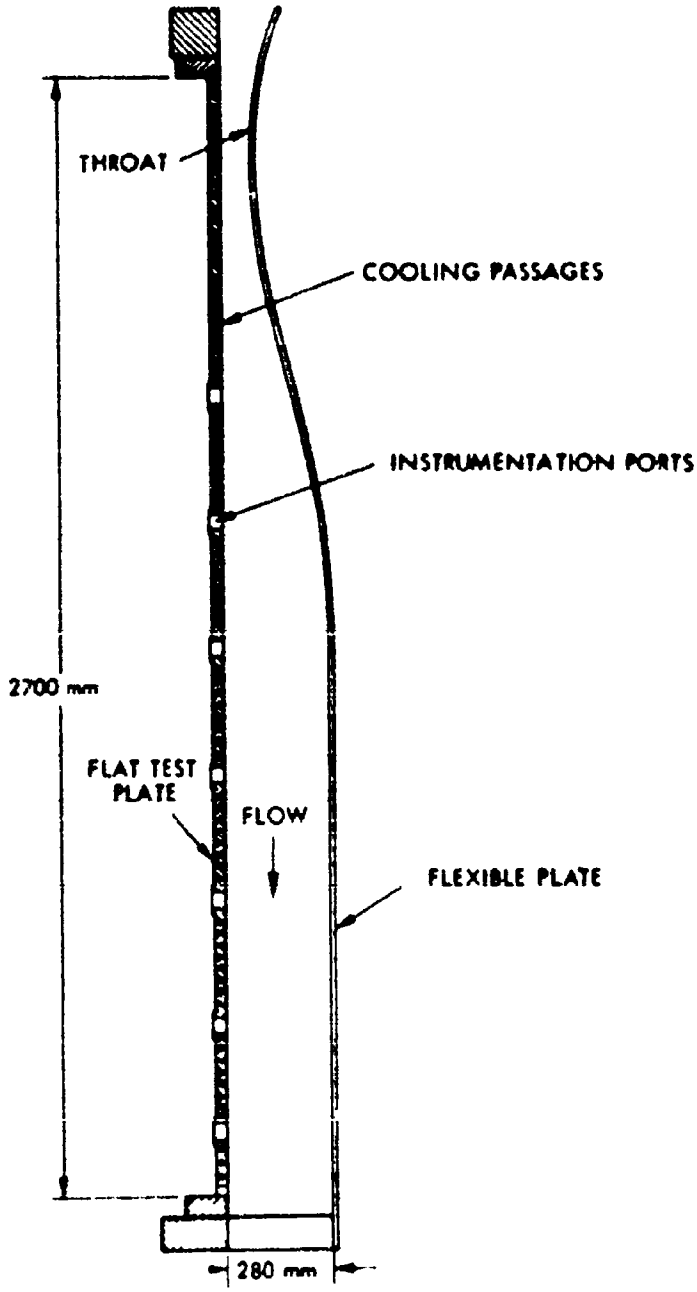

FIG. 6 NOL BOUNDARY LAYER CHANNEL

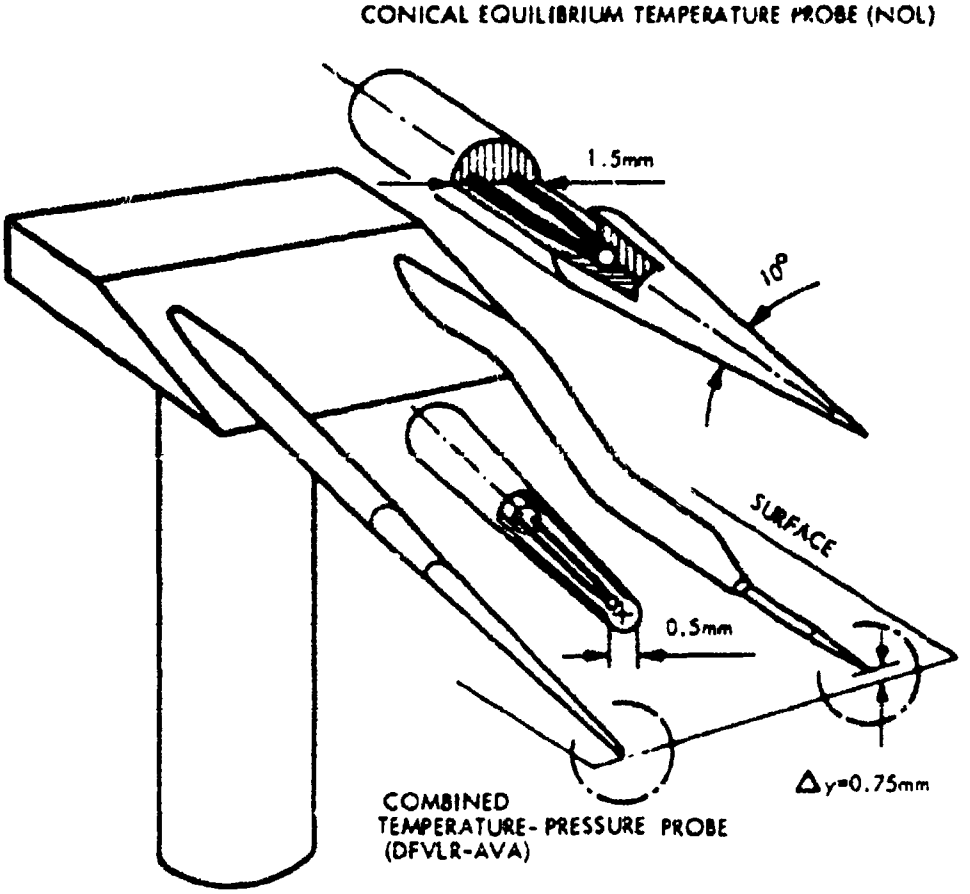

FIG. 7 ARRANGEMENT OF PROBES

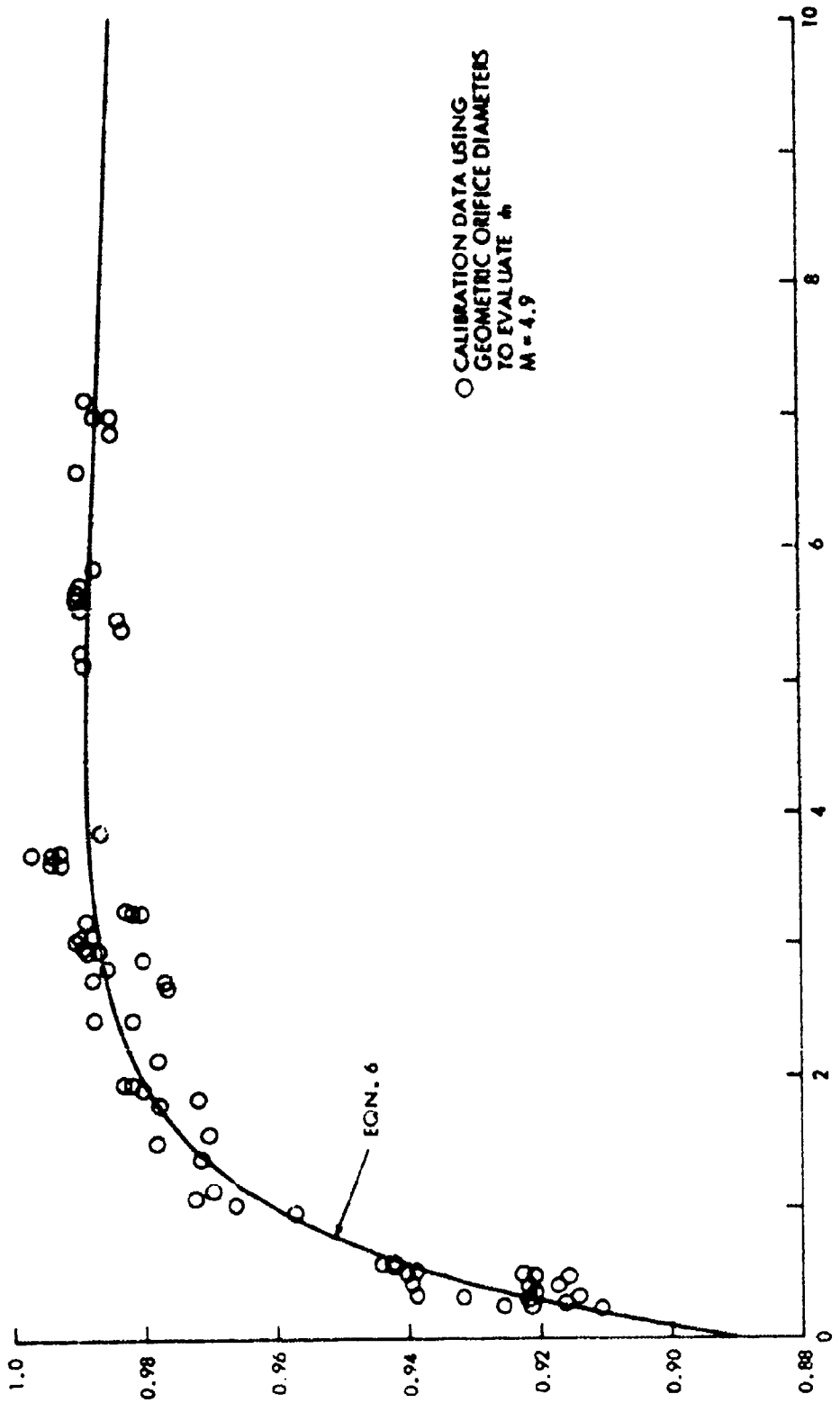

FIG. 8 RECOVERY FACTOR CALIBRATION CURVE FOR THE COMBINED TEMPERATURE-PRESSURE PROBE

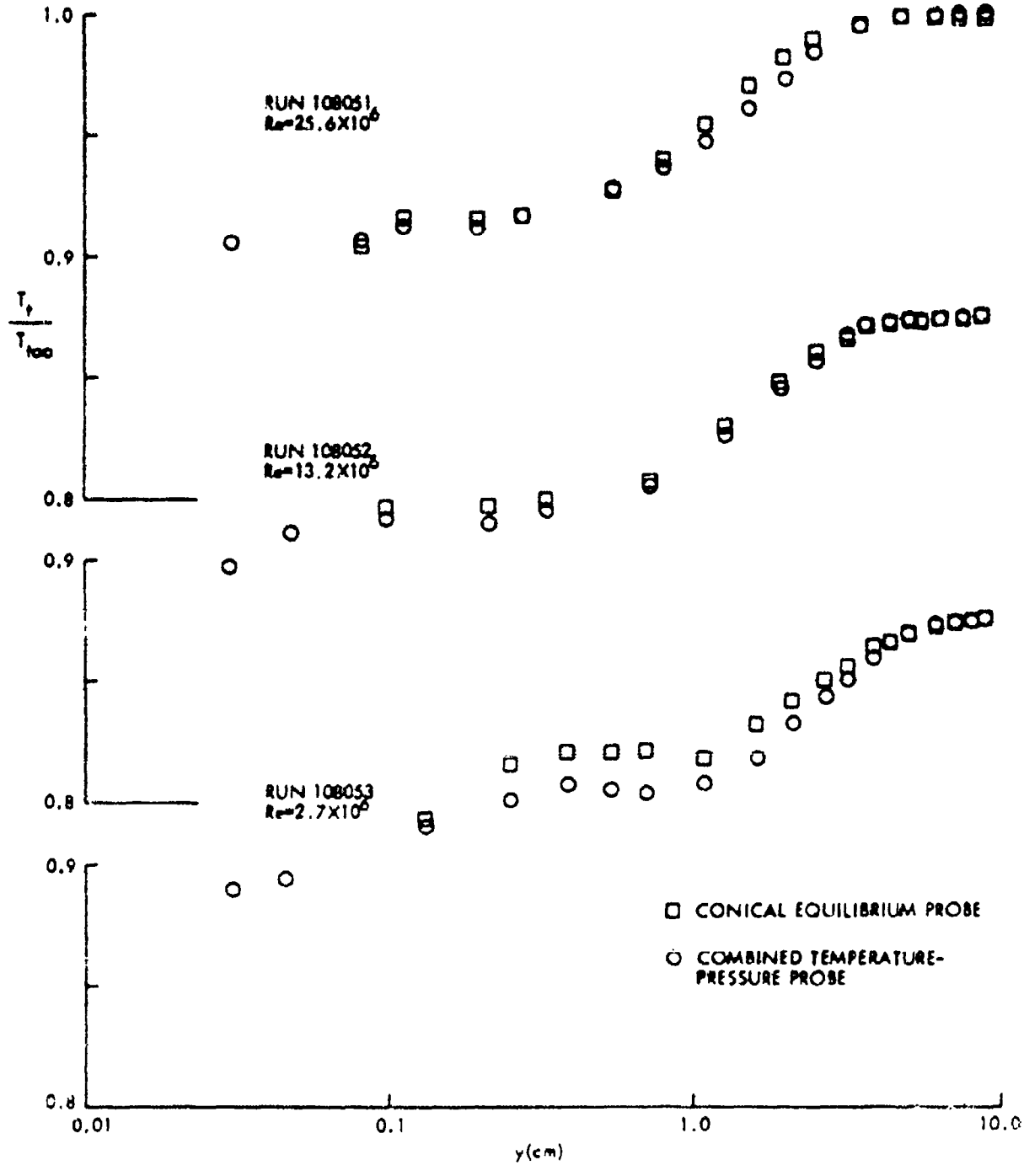

FIG. 9 COMPARATIVE TOTAL TEMPERATURE MEASUREMENTS, X=1.702, T_w/T_{aw}=1.0

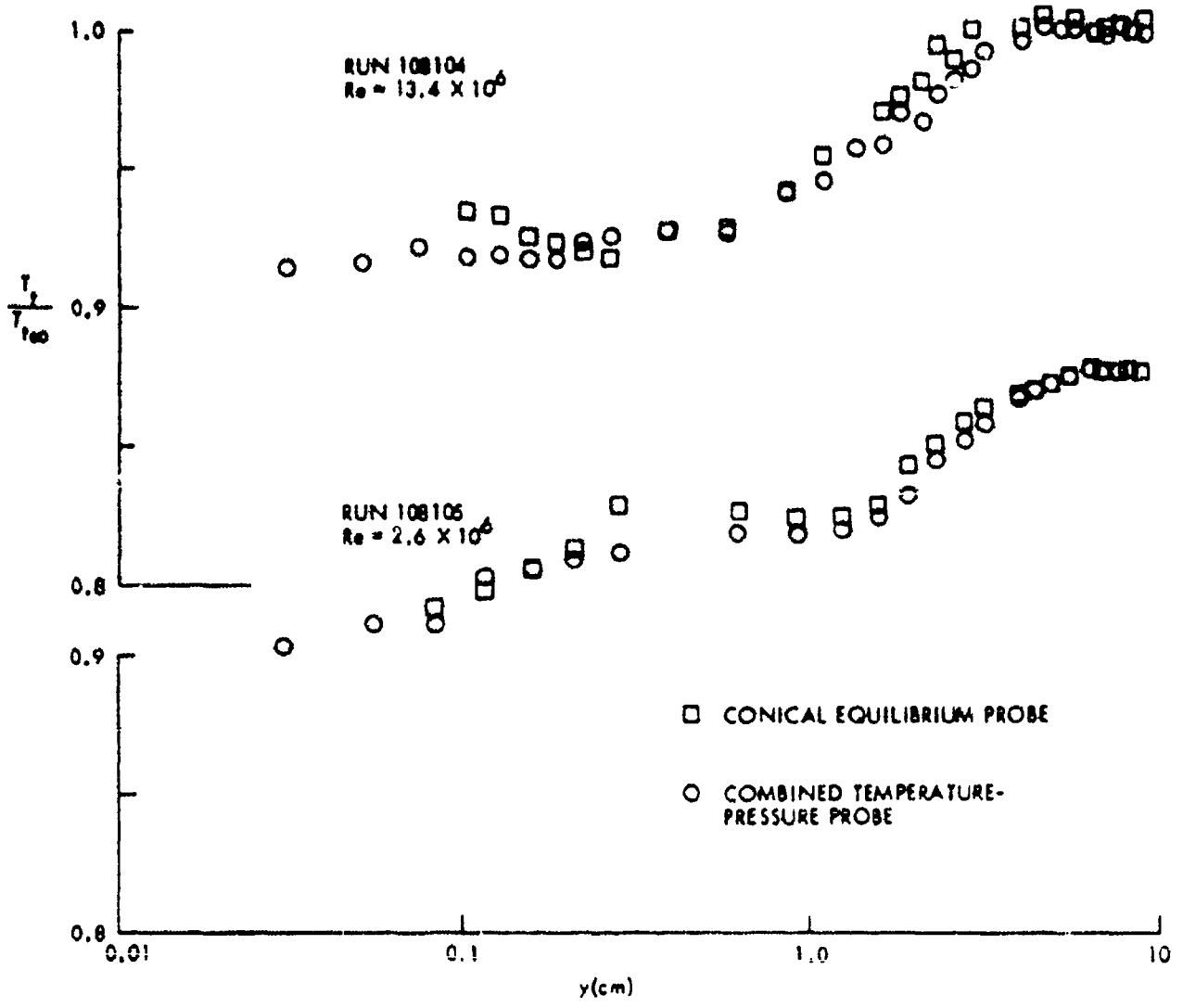

FIG. 10 COMPARATIVE TOTAL TEMPERATURE MEASUREMENTS X = 2.057, T_w/T_{aw} = 1.0

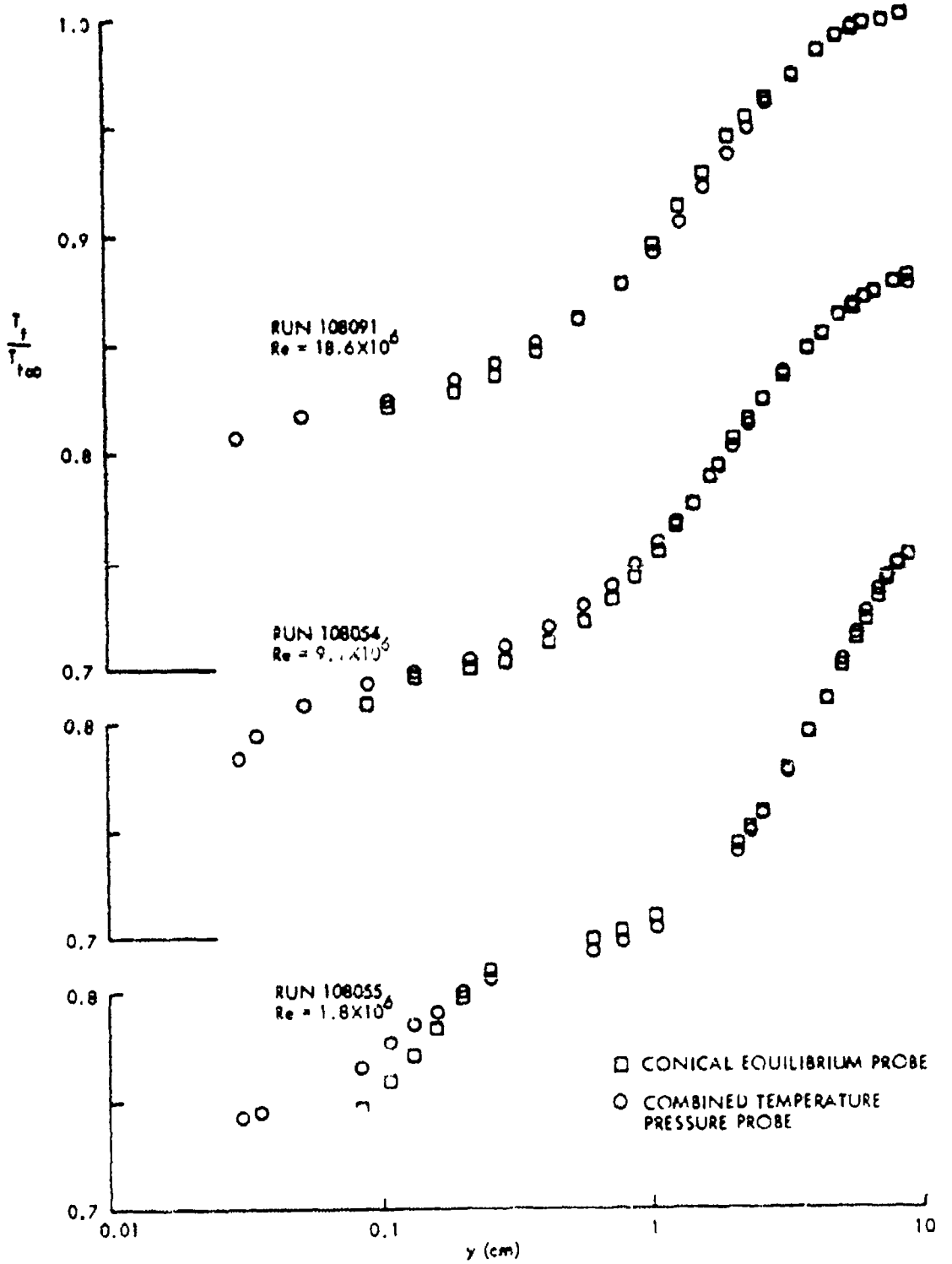

FIG. 11 COMPARATIVE TOTAL TEMPERATURE MEASUREMENTS, X = 1.702, T_w/T_{aw} = 0.8

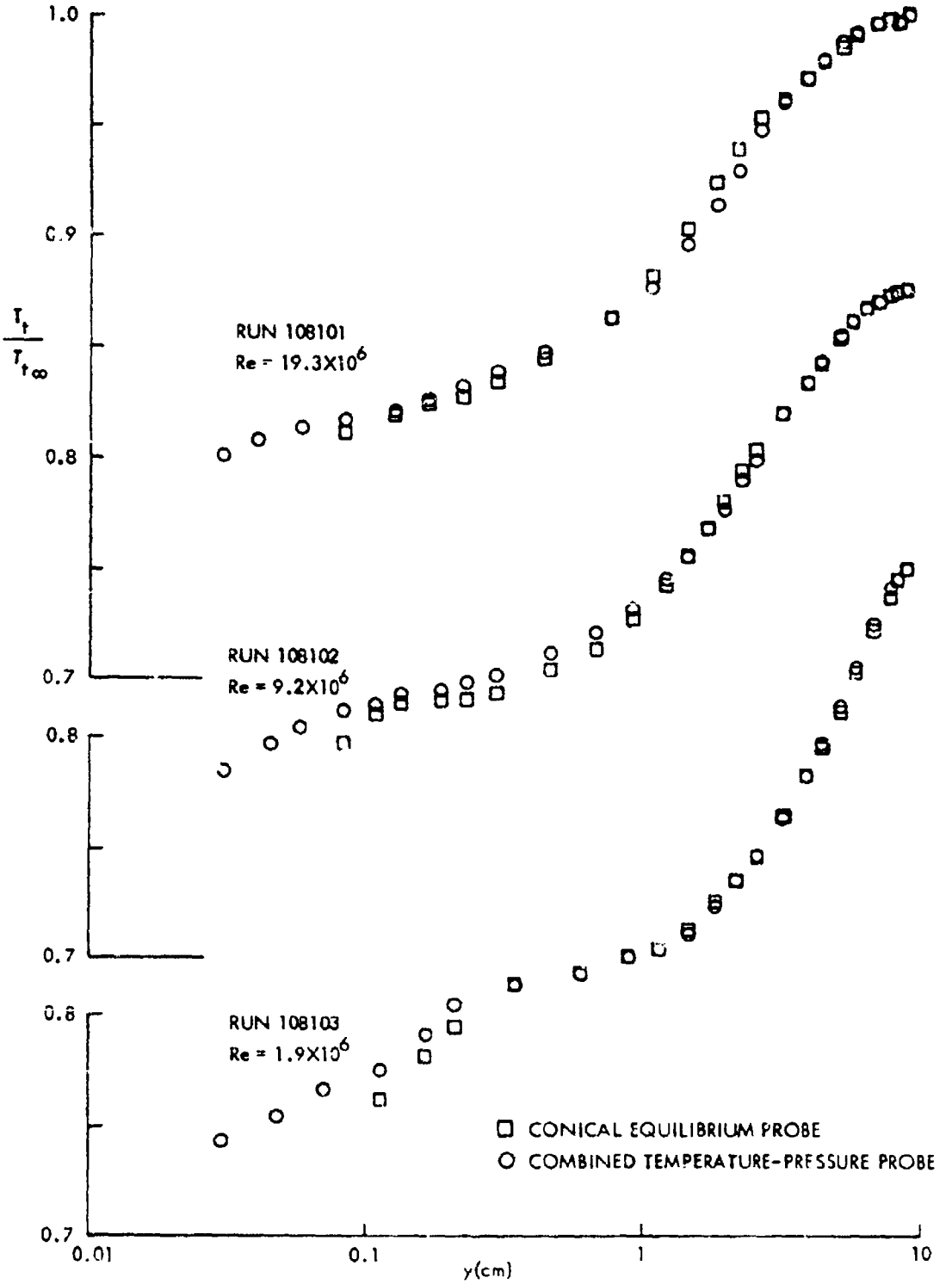

FIG. 12 COMPARATIVE TOTAL TEMPERATURE MEASUREMENTS
X = 2.057, T_w/T_{aw} = 0.8

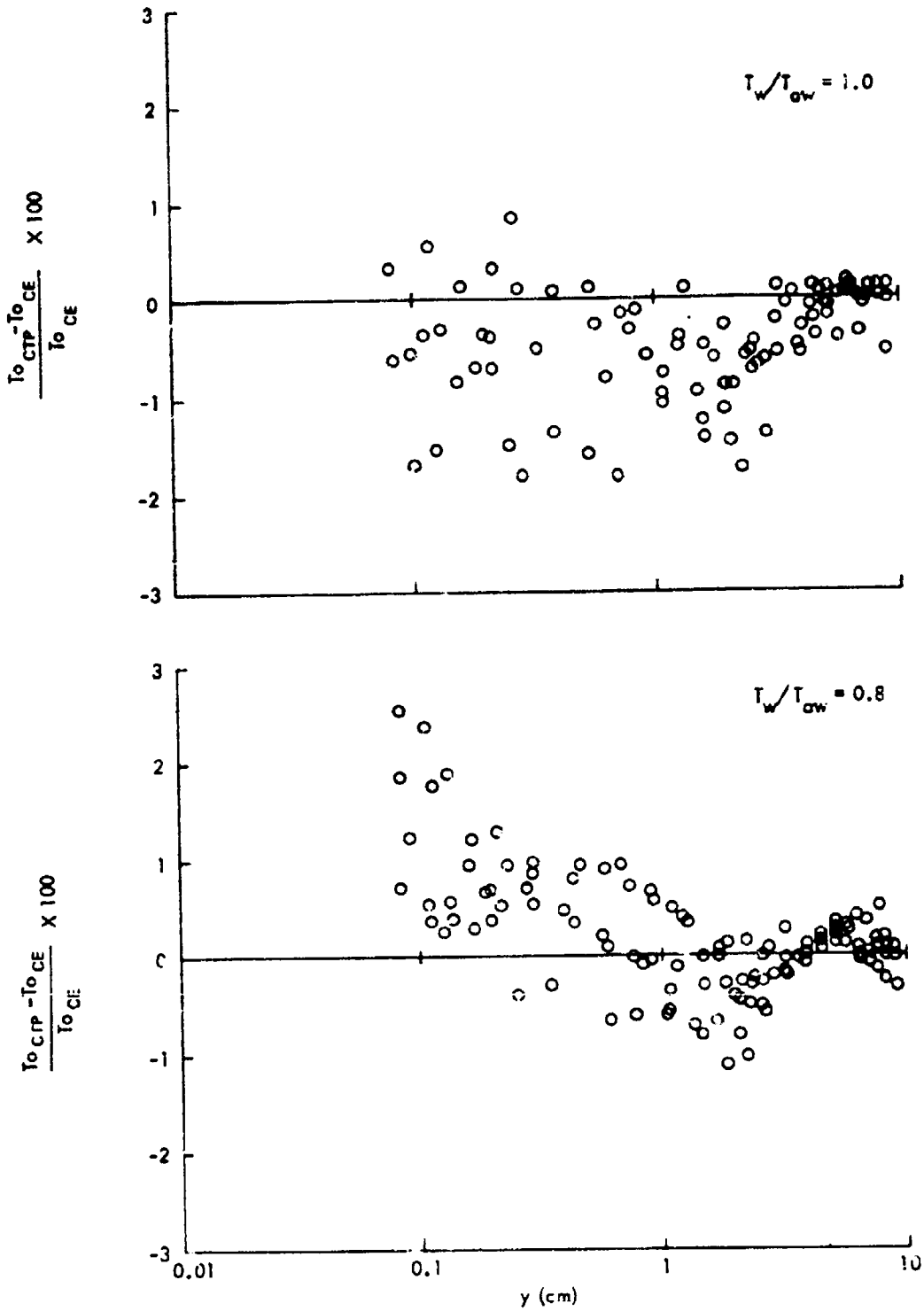

FIG. 3 PERCENTAGE DEVIATION OF THE COMPARATIVE TOTAL TEMPERATURE MEASUREMENTS

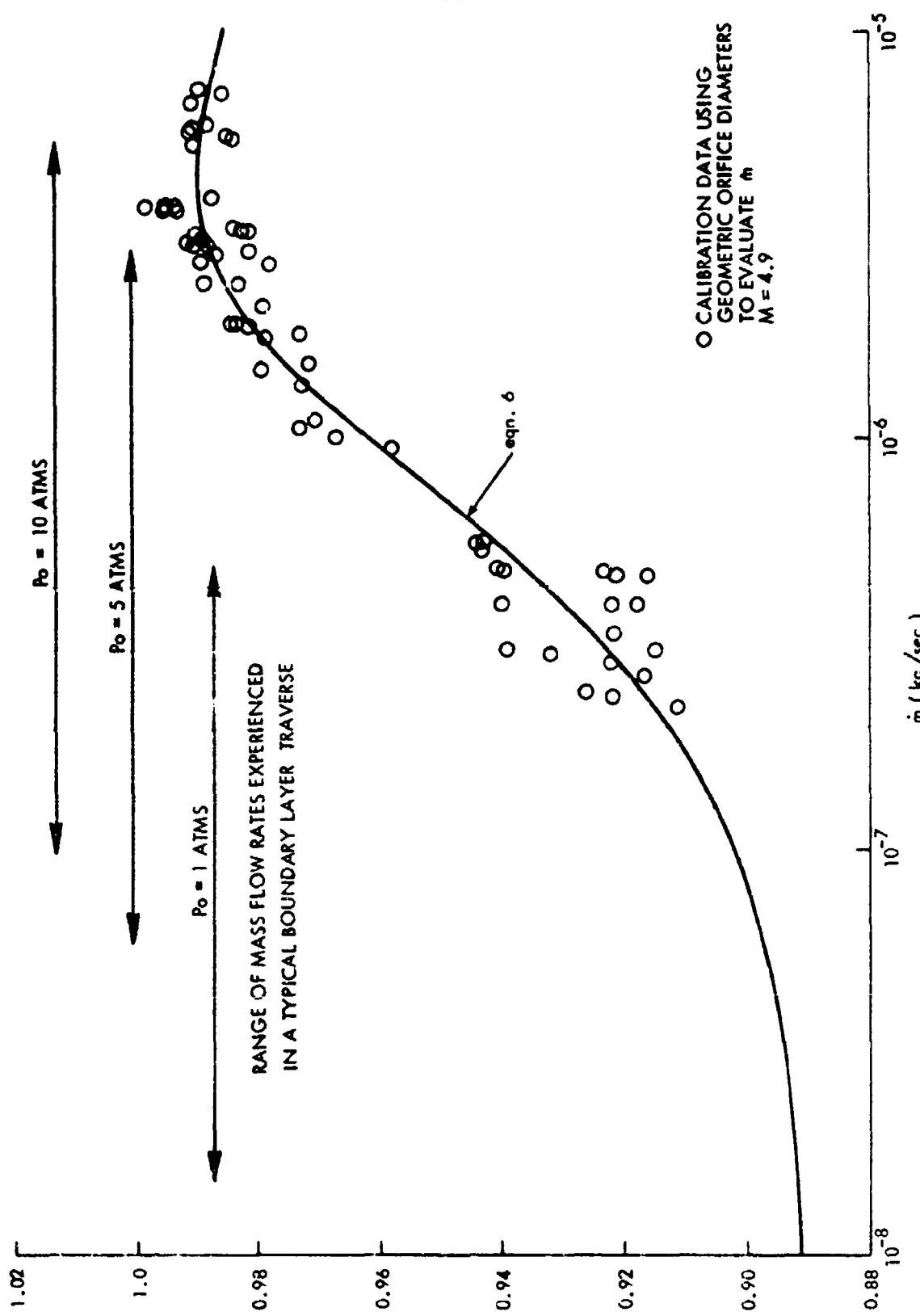

FIG. 14 RANGE OF APPLICATION OF THE COMBINED TEMPERATURE-PRESSURE PROBE RECOVERY FACTOR CALIBRATION

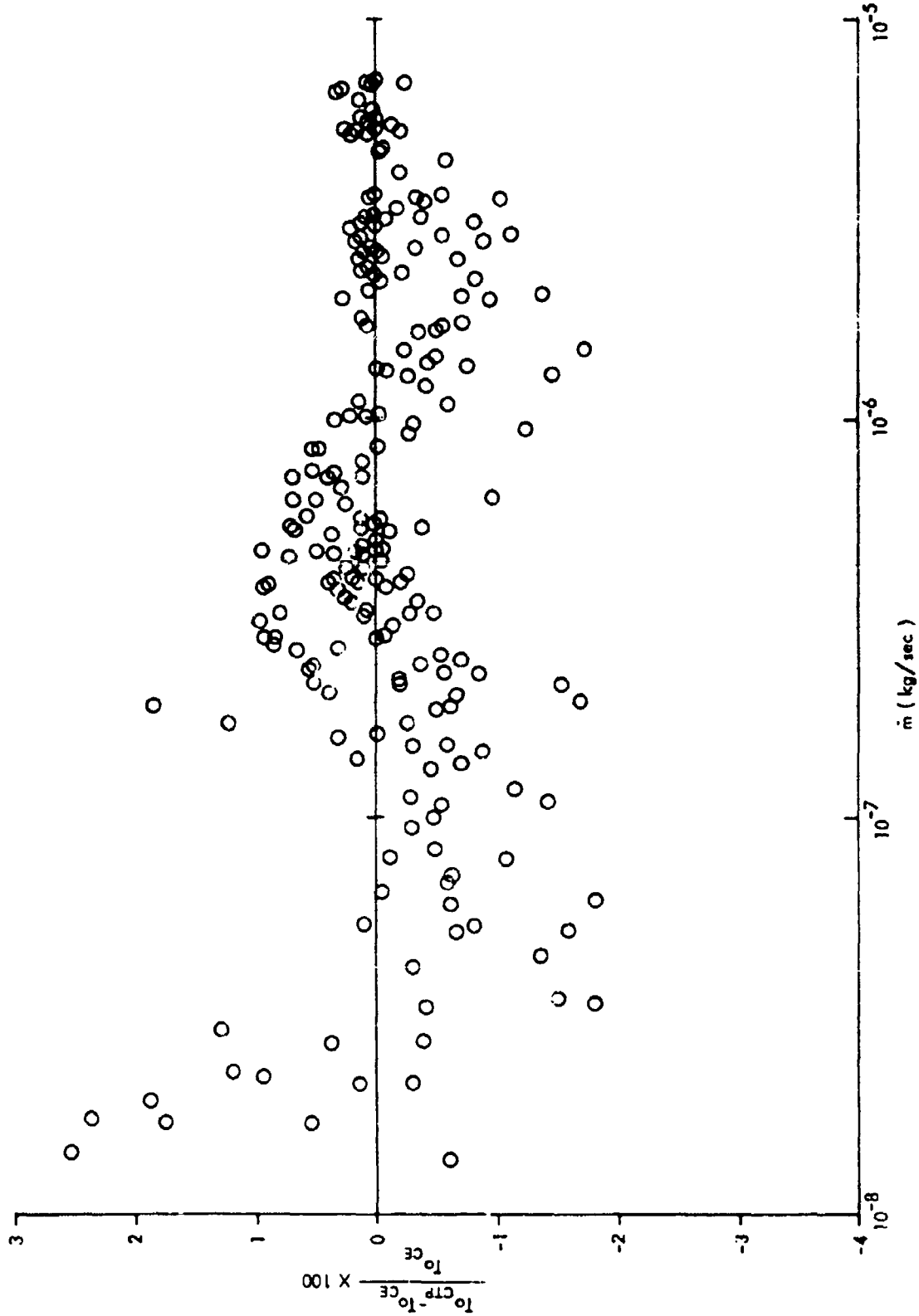

FIG. 15 PERCENTAGE DEVIATION IN COMPARATIVE TOTAL TEMPERATURE MEASUREMENTS AS A FUNCTION OF EXHAUSTED MASS FLUX

APPENDIX A

COMPUTER NOMENCLATURE

The nomenclature used in the computerized tabular output is defined as follows:

D	= ρ	= density
DE	= ρ_∞	= free-stream density
DEL	= δ	= boundary layer thickness
DSTR	= δ^*	= displacement thickness
M	= M	= local Mach number
ME	= M_∞	= free-stream Mach number
PO	= P_o	= tunnel supply pressure
PS	= P_s	= local static pressure
PSW	= P_{sw}	= local wall static pressure
RE	= $\frac{\rho_\infty u_\infty}{\mu_\infty}$	= free-stream Reynolds number per meter
STA	= x	= axial station
T	= T	= static temperature
TE	= T_∞	= free-stream static temperature
TW	= T_w	= wall temperature
TT	= T_t	= stagnation temperature
TTE	= T_{t_∞}	= free-stream stagnation temperature
TO	= T_o	= tunnel supply temperature
TH	= θ	= momentum thickness
THE	= θ_E	= energy thickness
THH	= θ_H	= enthalpy thickness

U	= u	= velocity
UE	= u_∞	= free-stream velocity
X	= x	= axial distance in flow direction measured from nozzle throat
Y	= y	= distance normal to flat plate surface

The units used in the computerized tabular output conform to the International Standard of Units (Ref. A-1) and are defined as:

ATM	= atmospheres
CM	= centimeters
DEG.K	= degrees Kelvin
KG/M3	= kilograms per meter cubed
M	= meters
M/S	= meters per second
N/M2	- newtons per meter squared

Two symbols are used in the profile data listing and are defined as:

*	= denotes boundary-layer thickness, δ, where $u/u_\infty = 0.995$
**	= denotes free-stream location

Reference

A-1 Mechtly, E. A., "The International System of Units." NASA SP-7012

APPENDIX B
TABULAR DATA

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108051 CONICAL EQUILIBRIUM TEMPERATURE PROBE

STA	= 1.702E+00		ME	= 4.788E+00		DEL	= 4.735E+00 CM
PO	= 1.030E+06	N/M2	DE	= 1.379E-01	KG/M3	DSTR	= 1.751E+00 CM
TO	= 3.381E+02	DEG.K	TE	= 6.053E+01	DEG.K	TH	= 1.743E-01 CM
PSW	= 2.363E+03	N/M2	UE	= 7.468E+02	M/S	THE	= 3.177E-01 CM
TW	= 2.959E+02	DEG.K	RE	= 2.562E+07	1/M	THH	= 4.153E-02 CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.8753	.2045	4.8890	0.0000
2	.0305	.8859	--	--	--	--
3	.0813	1.0380	.9040	.2407	4.1543	.4418
4	.1118	1.3021	.9160	.2617	3.8210	.5316
5	.1956	1.5331	.9157	.2874	3.4791	.5972
6	.2743	1.7165	.9168	.3104	3.2221	.6435
7	.5410	2.0293	.9284	.3516	2.8438	.7147
8	.7899	2.2988	.9401	.3917	2.5528	.7671
9	1.0846	2.6250	.9551	.4458	2.2432	.8211
10	1.5011	3.0853	.9712	.5353	1.8683	.8807
11	1.9634	3.5429	.9828	.6394	1.5648	.9252
12	2.4460	3.9449	.9900	.7437	1.3447	.9554
13	3.4417	4.4473	.9959	.8909	1.1224	.9840
* 14	4.7346	4.7119	.9992	.9748	1.0259	.9967
15	6.1189	4.7688	.9991	.9942	1.0058	.9988
** 16	7.3889	4.7883	1.0000	1.0000	1.0000	1.0000
17	8.2779	4.8222	1.0006	1.0111	.9890	1.0015
18	8.9383	4.8449	.9992	1.0203	.9801	1.0017

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108851 COMBINED TEMPERATURE-PRESSURE PROBE

STA	= 1.702E+00		ME	= 4.788E+00		DEL	= 4.735E+00 CM
PO	= 1.030E+06	N/M2	DE	= 1.382E-01	KG/M3	DSTR	= 1.746E+00 CM
TO	= 3.374E+02	DEG.K	TE	= 6.041E+01	DEG.K	TH	= 1.786E-01 CM
PSW	= 2.363E+03	N/M2	UE	= 7.461E+02	M/S	THE	= 3.256E-01 CM
TW	= 2.951E+02	DEG.K	RE	= 2.571E+07	1/M	THH	= 5.000E-02 CM

	N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
	1	0.0000	0.0000	.8746	.2047	4.8850	0.0000
	2	.0305	.8859	.9060	.2286	4.3743	.3869
	3	.0813	1.0380	.9069	.2399	4.1676	.4425
	4	.1118	1.3021	.9127	.2627	3.8069	.5306
	5	.1956	1.5331	.9125	.2884	3.4669	.5961
	6	.2743	1.7165	.9178	.3100	3.2257	.6438
	7	.5410	2.0293	.9295	.3512	2.8470	.7151
	8	.7899	2.2989	.9372	.3929	2.5451	.7659
	9	1.0846	2.6250	.9479	.4492	2.2264	.8180
	10	1.5011	3.0853	.9620	.5404	1.8504	.8765
	11	1.9634	3.5425	.9741	.6451	1.5502	.9211
	12	2.4460	3.9449	.9847	.7477	1.3374	.9528
	13	3.4417	4.4473	.9954	.8914	1.1219	.9838
*	14	4.7346	4.7119	.9999	.9741	1.0265	.9970
	15	6.1189	4.7688	.9998	.9935	1.0066	.9992
**	16	7.3889	4.7883	1.0000	1.0000	1.0000	1.0000
	17	8.2779	4.8222	1.0007	1.0110	.9892	1.0016
	18	8.9383	4.8449	1.0005	1.0191	.9813	1.0023

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108052 CONICAL EQUILIBRIUM TEMPERATURE PROBE

STA	= 1.702E+00		ME	= 4.831E+00		DEL	= 5.646E+00 CM
PO	= 5.164E+05	N/M2	DE	= 6.976E-02	KG/M3	DSTR	= 2.055E+00 CM
TO	= 3.380E+02	DEG.K	TE	= 5.966E+01	DEG.K	TH	= 2.009E-01 CM
PSW	= 1.195E+03	N/M2	UE	= 7.479E+02	M/S	THE	= 3.652E-01 CM
TW	= 2.954E+02	DEG.K	RE	= 1.320E+07	1/M	THH	= 4.890E-02 CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.8737	.2020	4.9511	0.0000
2	.0305	.6208	--	--	--	--
3	.0483	.9123	--	--	--	--
4	.0991	1.2813	.9210	.2545	3.9290	.5258
5	.2134	1.4548	.9212	.2727	3.6676	.5768
6	.3277	1.6739	.9245	.2979	3.3572	.6349
7	.7214	2.0612	.9313	.3505	2.8530	.7207
8	1.2802	2.5874	.9544	.4325	2.3122	.8145
9	1.9406	3.2204	.9724	.5578	1.7929	.8927
10	2.5425	3.7651	.9849	.6872	1.4552	.9403
11	3.1877	4.1691	.9907	.7973	1.2542	.9666
12	3.6957	4.4125	.9956	.8674	1.1528	.9808
13	4.4425	4.5954	.9969	.9246	1.0815	.9893
14	5.1105	4.6957	.9949	.9554	1.0463	.9943
• 15	5.6464	4.7456	.9975	.9737	1.0270	.9956
16	6.4872	4.7687	.9979	.9812	1.0192	.9966
17	7.6840	4.7934	.9983	.9890	1.0111	.9978
•• 18	8.8773	4.8305	1.0000	1.0000	1.0000	1.0000

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108052 COMBINED TEMPERATURE-PRESSURE PROBE

STA = 1.702E+00		ME = 4.831E+00		DEL = 5.646E+00	CM
PO = 5.164E+05	N/M2	DE = 6.956E-02	KG/M3	DSTR = 2.054E+00	CM
TO = 3.389E+02	DEG.K	TE = 5.981E+01	DEG.K	TH = 2.022E-01	CM
PSW = 1.195E+03	N/M2	UE = 7.489E+02	M/S	THE = 3.673E-01	CM
TW = 2.960E+02	DEG.K	RE = 1.314E+07	1/M	THH = 5.138E-02	CM

	N	Y(CM)	N	TT/TTE	D/DE	T/TE	U/UE
	1	0.0000	0.0000	.8734	.2020	4.9493	0.0000
	2	.0305	.6208	.8965	.2120	4.7166	.2791
	3	.0483	.9123	.9105	.2261	4.4235	.3972
	4	.0991	1.2813	.9160	.2559	3.9078	.5243
	5	.2134	1.4547	.9147	.2746	3.6417	.5747
	6	.3277	1.6739	.9199	.2993	3.3406	.6334
	7	.7214	2.0612	.9300	.3510	2.8492	.7203
	8	1.2802	2.5874	.9508	.4341	2.3035	.8130
	9	1.9406	3.2204	.9700	.5593	1.7880	.8915
	10	2.5425	3.7650	.9806	.6901	1.4490	.9382
	11	3.1877	4.1692	.9919	.7964	1.2556	.9671
	12	3.6957	4.4125	.9962	.8670	1.1534	.9811
	13	4.4425	4.5954	.9982	.9235	1.0829	.9900
	14	5.1105	4.6957	.9983	.9563	1.0456	.9940
•	15	5.6464	4.7457	.9979	.9734	1.0273	.9958
	16	6.4372	4.7688	.9988	.9803	1.0201	.9971
	17	7.6860	4.7934	.9995	.9879	1.0123	.9984
••	18	8.8773	4.8305	1.0000	1.0000	1.0000	1.0000

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108043 CONICAL EQUILIBRIUM TEMPERATURE PROBE

STA	= 1.702E+00		RE	= 4.785E+00		DEL	= 7.175E+00 CM
PO	= 1.004E+05	N/M2	DE	= 1.446E-02	KG/M3	DSTR	= 2.567E+00 CM
TO	= 3.382E+02	DEG.K	TE	= 6.061E+01	DEG.K	TH	= 2.547E-01 CM
PSW	= 2.441E+02	N/M2	UE	= 7.668E+02	M/S	THE	= 4.624E-01 CM
TW	= 2.982E+02	DEG.K	ME	= 2.684E+00	1/M	THH	= 4.667E-02 CM

N	Y(CM)	M	TT/TTE	U/UE	T/TE	U/UE
1	0.0000	0.0000	.8818	.2032	4.9204	0.0000
2	.0305	.4959	--	--	--	--
3	.0457	.5115	--	--	--	--
4	.1321	.9289	.9175	.2290	4.3661	.4054
5	.2499	1.3549	.9402	.2610	3.8312	.5554
6	.3810	1.5466	.9468	.2852	3.5067	.6704
7	.5309	1.7288	.9469	.3031	3.2998	.6543
8	.6883	1.8851	.9456	.3242	3.0864	.6918
9	1.0719	2.1227	.9424	.3616	2.7657	.7377
10	1.4002	2.5150	.9582	.4245	2.3555	.8066
11	2.0930	2.8874	.9655	.4952	2.0194	.8575
12	2.6804	3.3300	.9743	.5919	1.6894	.9065
13	3.1928	3.6908	.9803	.6809	1.4686	.9367
14	3.8532	4.0975	.9883	.7903	1.2653	.9632
15	4.3536	4.3039	.9905	.8513	1.1747	.9768
16	5.0775	4.4991	.9930	.9112	1.0975	.9850
17	5.1595	4.5746	.9960	.9681	1.0330	.9934
* 18	7.1755	4.7329	.9984	.9837	1.0165	.9972
19	8.1382	4.7562	.9990	.9906	1.0097	.9983
** 21	9.0449	4.7852	1.0000	1.0000	1.0000	1.0000

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108053 COMBINED TEMPERATURE-PRESSURE PROBE

STA	=	1.702E+00		ME	=	4.785E+00	DEL	= 7.175E+00 CM
PO	=	1.004E+05	N/M2	DE	=	1.441E-02 KG/M3	DSTR	= 2.561E+00 CM
TO	=	3.396E+02	DEG.K	TE	=	6.066E+01 DEG.K	TH	= 2.689E-01 CM
PSW	=	2.441E+02	N/M2	UE	=	7.483E+02 M/S	THE	= 4.727E-01 CM
TW	=	2.976E+02	DEG.K	RE	=	2.666E+06 1/M	THH	= 7.870E-02 CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.8763	.2045	4.8893	0.0000
2	.0305	.4959	.8890	.2115	4.7279	.2253
3	.0457	.5115	.8932	.2111	4.7360	.2326
4	.1321	.9288	.9147	.2297	4.3527	.4050
5	.2489	1.3588	.9261	.2650	3.7739	.5516
6	.3810	1.5864	.9319	.2891	3.4588	.6166
7	.5309	1.7287	.9299	.3079	3.2475	.6510
8	.6883	1.8851	.9284	.3002	3.0280	.6855
9	1.0719	2.1227	.9323	.3655	2.7361	.7338
10	1.6802	2.5149	.9426	.4306	2.3221	.8009
11	2.0930	2.8874	.9569	.4996	2.0015	.8537
12	2.6848	3.3300	.9678	.5959	1.6783	.9015
13	3.1928	3.6909	.9750	.6846	1.4606	.9322
14	3.8532	4.0975	.9836	.7941	1.2594	.9609
15	4.3536	4.3039	.9898	.8519	1.1739	.9745
16	5.0775	4.4991	.9940	.9103	1.0986	.9855
17	6.1595	4.6796	.9977	.9664	1.0347	.9948
* 18	7.1755	4.7329	.9979	.9843	1.0160	.9969
19	8.1382	4.7542	.9990	.9903	1.0097	.9986
** 20	9.0449	4.7852	1.0000	1.0000	1.0000	1.0000

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108104 CONICAL EQUILIBRIUM TEMPERATURE PROBE

STA	=	2.057E+00		RE	=	6.907E+00	DEL	= 5.654E+00 CM
PO	=	5.171E+05	N/M2	UE	=	6.836E-02 KG/M3	DSTR	= 2.262E+00 CM
TO	=	3.388E+02	DEG.K	TE	=	5.825E+01 DEG.K	TH	= 2.047E-01 CM
PSW	=	1.132E+03	N/M2	UE	=	7.508E+02 M/S	THF	= 3.715E-01 CM
TW	=	2.996E+02	DEG.K	RE	=	1.335E+07 1/M	THH	= 3.208E-02 CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.4844	.1944	5.1432	0.0000
2	.0305	.8131	--	--	--	--
3	.0508	1.0033	--	--	--	--
4	.0737	1.2272	--	--	--	--
5	.1018	1.3353	.9329	.2501	3.9992	.5442
6	.1245	1.4013	.9315	.2571	3.8896	.5632
7	.1524	1.4670	.9237	.2641	3.7866	.5734
8	.1829	1.4938	.9219	.2697	3.7073	.5861
9	.2184	1.5445	.9190	.2768	3.6124	.5998
10	.2616	1.5982	.9164	.2835	3.5277	.6117
11	.3435	1.7180	.9261	.2953	3.3869	.6463
12	.5664	1.8839	.9276	.3169	3.1553	.6820
13	.8382	2.1076	.9408	.3451	2.8974	.7311
14	1.0719	2.2881	.9528	.3694	2.7071	.7672
15	1.3259	2.5029	.9549	.4057	2.4651	.8004
16	1.5748	2.7128	.9687	.4388	2.2791	.8346
17	1.7755	2.8912	.9762	.4715	2.1207	.8580
18	2.0498	3.1300	.9796	.5194	1.9252	.8850
19	2.2708	3.3149	.9923	.5553	1.8009	.9079
20	2.5249	3.5503	.9876	.6130	1.6314	.9241
21	2.8499	3.8199	.9979	.6752	1.4811	.9474
22	3.0836	4.0267	.9922	.7353	1.3601	.9570
23	3.9472	4.4389	.9969	.8505	1.1758	.9809
24	4.5695	4.6256	1.0031	.9049	1.1050	.9909
25	5.1141	4.7447	.9999	.9402	1.0569	.9960
* 26	5.6591	4.8249	1.0027	.9699	1.0310	.9986
27	6.4110	4.9706	.9971	.9906	1.0095	.9973
28	6.9317	4.8817	.9996	.9919	1.0082	.9989
** 29	7.6886	4.9071	1.0000	1.0000	1.0000	1.0000
30	8.2677	4.9161	.9973	1.0054	.9943	.9990
31	8.9154	4.9294	1.0018	1.0057	.9963	1.0017

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108104 COMBINED TEMPERATURE-PRESSURE PROBE

STA	= 2.057E+00		ME	= 4.907E+00		DEL	= 5.659E+00 CM
PO	= 5.171E+05	N/M2	DE	= 6.868E-02	KG/M3	DSTR	= 2.253E+00 CM
TO	= 3.372E+02	DEG.K	TE	= 5.797E+01	DEG.K	TH	= 2.138E-01 CM
PSW	= 1.132E+03	N/M2	UE	= 7.490E+02	M/S	THE	= 3.884E-01 CM
TW	= 2.979E+02	DEG.K	RE	= 1.345E+07	1/M	THH	= 5.000E-02 CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.8836	.1946	5.1388	0.0000
2	.0305	.8131	.9128	.2133	4.6887	.3588
3	.0508	1.0033	.9149	.2258	4.4292	.4303
4	.0737	1.2272	.9203	.2431	4.1134	.5072
5	.1016	1.3353	.9171	.2543	3.9316	.5396
6	.1245	1.4013	.9172	.2611	3.8299	.5589
7	.1524	1.4470	.9159	.2663	3.7545	.5714
8	.1829	1.4938	.9155	.2716	3.6815	.5841
9	.2184	1.5485	.9219	.2760	3.6238	.6007
10	.2616	1.5982	.9241	.2811	3.5571	.6143
11	.3835	1.7180	.9269	.2950	3.3898	.6446
12	.5664	1.8839	.9252	.3178	3.1471	.6811
13	.8382	2.1076	.9398	.3455	2.8944	.7307
14	1.0719	2.2880	.9436	.3730	2.6809	.7634
15	1.3259	2.5029	.9560	.4052	2.4678	.8013
16	1.5748	2.7128	.9567	.4442	2.2510	.8294
17	1.7755	2.8912	.9684	.4744	2.1080	.8554
18	2.0498	3.1299	.9653	.5271	1.8971	.8785
19	2.2708	3.3200	.9751	.5650	1.7698	.9001
20	2.5248	3.5503	.9805	.6174	1.6196	.9207
21	2.8499	3.8200	.9841	.6846	1.4606	.9408
22	3.0836	4.0267	.9901	.7368	1.3571	.9560
23	3.9472	4.4389	.9934	.8552	1.1693	.9782
24	4.5695	4.6256	.9993	.9083	1.1009	.9891
25	5.1181	4.7448	.9982	.9478	1.0551	.9932
* 26	5.6591	4.8249	.9987	.9737	1.0270	.9964
27	6.4110	4.8706	.9977	.9901	1.0100	.9975
28	6.9317	4.8817	.9962	.9952	1.0048	.9972
** 29	7.6886	4.9071	1.0000	1.0000	1.0000	1.0000
30	8.2677	4.9161	.9976	1.0055	.9946	.9991
31	8.9154	4.9295	.9964	1.0112	.9889	.9990

NCL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108105 CONICAL EQUILIBRIUM TEMPERATURE PROBE

STA = 2.057E+00		ME = 4.756E+00		DEL = 6.411E+00	CM
PO = 1.024E+05	N/M2	DE = 1.409E-02	KG/M3	DSTR = 2.856E+00	CM
TO = 3.390E+02	DEG.K	TE = 6.137E+01	DEG.K	TH = 2.674E-01	CM
PSW = 2.467E+02	N/M2	UE = 7.469E+02	M/S	THE = 4.812E-01	CM
TW = 3.023E+02	DEG.K	RE = 2.577E+06	1/M	THH = 4.444E-02	CM

N	Y(CM)	M	IT/ITE	O/DE	T/TE	U/UE
1	0.0000	0.0000	.8919	.2030	4.9263	0.0000
2	.0305	.3721	--	--	--	--
3	.0559	.4481	--	--	--	--
4	.0838	.6077	.9156	.2124	4.7092	.2773
5	.1168	.7920	.9219	.2210	4.5242	.3542
6	.1600	.9830	.9289	.2326	4.3000	.4286
7	.2108	1.1769	.9367	.2468	4.0512	.4981
8	.2819	1.3616	.9524	.2606	3.8375	.5609
9	.6223	1.6999	.9501	.3007	3.3257	.6518
10	.9271	1.9235	.9472	.3326	3.0069	.7014
11	1.2497	2.1075	.9482	.3605	2.7736	.7368
12	1.5850	2.3095	.9524	.3929	2.5452	.7749
13	1.9279	2.5126	.9665	.4238	2.3594	.8115
14	2.3190	2.7863	.9739	.4746	2.1072	.8505
15	2.7940	3.0739	.9815	.5330	1.8761	.8853
16	3.1953	3.3441	.9867	.5939	1.6839	.9125
17	4.0107	3.8511	.9932	.7230	1.3831	.9523
18	4.4856	4.1281	.9949	.8022	1.2466	.9692
19	4.9657	4.3428	.9962	.8673	1.1530	.9806
20	5.6439	4.5206	.9982	.9260	1.0709	.9900
* 21	6.4110	4.6636	.9997	.9689	1.0 [illegible]	.9962
22	6.9037	4.7229	.9998	.9889	1.0 [illegible]	.9986
** 23	7.6987	4.7557	1.0000	1.0000	1.0 [illegible]	1.0000
24	8.2042	4.7678	.9997	1.0044	[illegible]	1.0003
25	8.9078	4.7737	.9997	1.0065	[illegible]	1.0005

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108105 COMBINED TEMPERATURE-PRESSURE PROBE

STA = 2.057E+00		ME = 4.756E+00		DEL = 6.411E+00	CM
PO = 1.034E+05	N/M2	DE = 1.407E-02	KG/M3	DSTR = 2.852E+00	CM
TO = 3.394E+02	DEG.K	TE = 6.145E+01	DEG.K	TH = 2.722E-01	CM
PSW = 2.467E+02	N/M2	UE = 7.473E+02	M/S	THE = 4.895E-01	CM
TW = 3.023E+02	DEG.K	RE = 2.571E+06	1/M	THH = 5.399E-02	CM

	N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
	1	0.0000	0.0000	.8908	.2032	4.9203	0.0000
	2	.0305	.3720	.9019	.2063	4.8472	.1722
	3	.0559	.4480	.9100	.2069	4.8324	.2071
	4	.0838	.6077	.9100	.2136	4.6907	.2765
	5	.1168	.7920	.9270	.2198	4.5496	.3552
	6	.1600	.9830	.9302	.2322	4.3059	.4289
	7	.2108	1.1769	.9331	.2478	4.0359	.4972
	8	.2819	1.3616	.9352	.2654	3.7683	.5558
	9	.6223	1.6999	.9424	.3031	3.2992	.6492
	10	.9271	1.9235	.9417	.3345	2.9894	.6993
	11	1.2497	2.1074	.9436	.3623	2.7601	.7362
	12	1.5850	2.3095	.9479	.3947	2.5333	.7730
	13	1.9279	2.5125	.9555	.4287	2.3327	.8069
	14	2.3190	2.7862	.9682	.4773	2.0950	.8480
	15	2.7940	3.0739	.9754	.5364	1.8643	.8825
	16	3.1953	3.3441	.9812	.5972	1.6744	.9099
	17	4.0107	3.8511	.9904	.7251	1.3792	.9510
	18	4.4856	4.1281	.9929	.8039	1.2440	.9682
	19	4.9657	4.3427	.9958	.8676	1.1526	.9804
	20	5.6439	4.5305	.9982	.9259	1.0800	.9900
*	21	6.4110	4.6635	1.0010	.9676	1.0335	.9969
	22	6.9037	4.7229	1.0000	.9883	1.0114	.9987
**	23	7.6987	4.7557	1.0000	1.0000	1.0000	1.0000
	24	8.2042	4.7678	1.0009	1.0032	.9968	1.0009
	25	8.9078	4.7737	.9995	1.0067	.9934	1.0005

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 104091 CONICAL EQUILIBRIUM TEMPERATURE PROBE

STA = 1.702E+00		ME = 4.914E+00		DEL = 6.510E+00	CM
PO = 1.031E+06	N/M2	DE = 1.101E-01	KG/M3	DSTR = 1.814E+00	CM
TO = 4.255E+02	DEG.K	TE = 7.299E+01	DEG.K	TH = 2.419E-01	CM
PSW = 2.294E+03	N/M2	UE = 8.416E+02	M/S	THE = 4.455E-01	CM
TW = 3.030E+02	DEG.K	RE = 1.867E+07	1/M	THH = 1.596E-01	CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.7121	.2609	4.1511	0.0000
2	.0305	1.1854	--	--	--	--
3	.0533	1.3890	--	--	--	--
4	.1118	1.5790	.8201	.3135	3.1898	.5739
5	.1981	1.7307	.8271	.3316	3.0152	.6116
6	.2794	1.8387	.8345	.3446	2.9022	.6374
7	.3937	1.9906	.8454	.3637	2.7493	.6717
8	.5664	2.1868	.8588	.3908	2.5589	.7119
9	.8179	2.4543	.8767	.4314	2.3180	.7604
10	1.0719	2.7288	.8945	.4774	2.0946	.8037
11	1.3437	3.0201	.9116	.5315	1.8815	.8430
12	1.6485	3.3342	.9273	.5963	1.6769	.8787
13	2.0422	3.7019	.9438	.6799	1.4707	.9136
14	2.3927	3.9890	.9530	.7529	1.3283	.9356
15	2.8346	4.2314	.9620	.8169	1.2241	.9527
16	3.5662	4.4896	.9725	.8875	1.1268	.9698
17	4.4450	4.6987	.9820	.9461	1.0570	.9831
18	5.1410	4.7706	.9890	.9630	1.0384	.9893
19	5.8801	4.8130	.9925	.9736	1.0271	.9927
* 20	6.5100	4.8399	.9962	.9790	1.0215	.9955
21	7.6048	4.8645	.9983	.9851	1.0151	.9974
** 22	8.9078	4.9139	1.0000	1.0000	1.0000	1.0000

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108091 COMBINED TEMPERATURE-PRESSURE PROBE

STA = 1.702E+00		ME = 4.914E+00		DEL = 6.510E+00	CM
PO = 1.031E+06	N/M2	DE = 1.098E-01	KG/M3	DSTR = 1.813E+00	CM
TO = 4.266E+02	DEG.K	TE = 7.319E+01	DEG.K	TH = 2.428E-01	CM
PSW = 2.296E+03	N/M2	UE = 8.427E+02	M/S	THE = 4.470E-01	CM
TW = 3.039E+02	DEG.K	RE = 1.859E+07	1/M	THH = 1.613E-01	CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.7123	.2408	4.1522	0.0000
2	.0305	1.1854	.8065	.2725	3.6698	.4621
3	.0533	1.3891	.8161	.2913	3.4328	.5237
4	.1118	1.5790	.8231	.3124	3.2015	.5750
5	.1981	1.7307	.8328	.3294	3.0359	.6137
6	.2794	1.8386	.8403	.3422	2.9225	.6396
7	.3937	1.9906	.8494	.3620	2.7624	.6733
8	.5664	2.1868	.8606	.3900	2.5642	.7126
9	.8179	2.4543	.8759	.4318	2.3160	.7601
10	1.0719	2.7288	.8914	.4790	2.0875	.8023
11	1.3437	3.0201	.9051	.5353	1.8681	.8400
12	1.6485	3.3343	.9210	.6004	1.6656	.8757
13	2.0422	3.7020	.9361	.6855	1.4587	.9099
14	2.3927	3.9891	.9483	.7566	1.3217	.9333
15	2.8346	4.2315	.9601	.8185	1.2217	.9518
16	3.5662	4.4896	.9722	.8877	1.1265	.9697
17	4.4450	4.6987	.9840	.9441	1.0592	.9841
18	5.1410	4.7706	.9905	.9615	1.0400	.9901
19	5.8801	4.8130	.9951	.9711	1.0298	.9939
* 20	6.5100	4.8399	.9961	.9791	1.0214	.9954
21	7.6048	4.8645	.9969	.9865	1.0137	.9967
** 22	8.9078	4.9140	1.0000	1.0000	1.0000	1.0000

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108054 CONICAL EQUILIBRIUM TEMPERATURE PROBE

STA	=	1.702E+00	RE	=	4.875E+00	DEL	=	4.883E+00 CM
PO	=	5.178E+05 N/M2	DE	=	5.408E-02 KG/M3	DSTR	=	1.958E+00 CM
TO	=	4.230E+02 DEG.K	TE	=	7.352E+01 DEG.K	TH	=	2.723E-01 CM
PSW	=	1.135E+03 N/M2	UE	=	8.380E+02 M/S	THE	=	4.981E-01 CM
TW	=	3.004E+02 DEG.K	RE	=	9.064E+06 1/M	THH	=	1.916E-01 CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.7102	.2667	4.0863	0.0000
2	.0305	.8178	--	--	--	--
3	.0356	.9670	--	--	--	--
4	.0533	1.1797	--	--	--	--
5	.0914	1.3976	.8073	.2994	3.3401	.5239
6	.1372	1.5270	.8149	.3112	3.2133	.5615
7	.2184	1.6550	.8233	.3267	3.0606	.5938
8	.2946	1.7611	.8264	.3378	2.9605	.6144
9	.4318	1.8946	.8357	.3573	2.7990	.6501
10	.5796	2.0406	.8442	.3773	2.6503	.6814
11	.7315	2.1901	.8546	.3965	2.5097	.7116
12	.8915	2.3426	.8645	.4217	2.3716	.7399
13	1.0871	2.5365	.8763	.4535	2.2050	.7725
14	1.2675	2.7152	.8872	.4847	2.0631	.7999
15	1.4707	2.9107	.8983	.5213	1.9184	.8269
16	1.6967	3.1284	.9097	.5650	1.7699	.8536
17	1.8339	3.2531	.9144	.5923	1.6882	.8670
18	2.0879	3.4781	.9276	.6408	1.5605	.8917
19	2.3597	3.7155	.9367	.6978	1.4332	.9123
20	2.7026	3.9672	.9456	.7623	1.3118	.9320
21	3.1801	4.2499	.9562	.8383	1.1929	.9521
22	3.9624	4.5291	.9697	.9145	1.0934	.9714
23	4.4704	4.6328	.9762	.9423	1.0613	.9784
24	5.1308	4.7307	.9840	.9671	1.0340	.9847
25	5.7531	4.7802	.9868	.9790	1.0214	.9909
26	6.3957	4.8109	.9938	.9843	1.0159	.9946
* 27	6.8834	4.8335	.9961	.9897	1.0104	.9966
** 28	8.1382	4.8754	1.0000	1.0000	1.0000	1.0000
29	9.1745	4.9174	1.0033	1.0110	.9892	1.0031

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108054 COMBINED TEMPERATURE-PRESSURE PROBE

STA	= 1.702E+00		ME	= 4.875E+00		DEL	= 6.883E+00 CM
PO	= 5.178E+05	N/M2	DE	= 5.435E-02	KG/M3	DSTR	= 1.961E+00 CM
TO	= 4.209E+02	DEG.K	TE	= 7.315E+01	DEG.K	TH	= 2.697E-01 CM
PSW	= 1.135E+03	N/M2	UE	= 8.359E+02	M/S	THE	= 4.936E-01 CM
TW	= 3.000E+02	DEG.K	RE	= 9.137E+06	1/M	THH	= 1.866E-01 CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.7128	.2438	4.1017	0.0000
2	.0305	.8178	.7830	.2516	3.9739	.3344
3	.0356	.9670	.7932	.2601	3.8450	.3889
4	.0533	1.1797	.8071	.2753	3.6327	.4612
5	.0914	1.3976	.8172	.2957	3.3814	.5271
6	.1372	1.5270	.8221	.3100	3.2257	.5625
7	.2184	1.6550	.8276	.3250	3.0767	.5954
8	.2946	1.7411	.8334	.3349	2.9856	.6170
9	.4318	1.8946	.8424	.3544	2.8216	.6527
10	.5766	2.0406	.8518	.3739	2.6743	.6844
11	.7315	2.1901	.8608	.3956	2.5281	.7142
12	.8915	2.3426	.8703	.4189	2.3874	.7424
13	1.0871	2.5365	.8807	.4513	2.2159	.7745
14	1.2675	2.7152	.8903	.4831	2.0702	.8013
15	1.4707	2.9107	.8982	.5214	1.9180	.8268
16	1.6967	3.1283	.9104	.5645	1.7715	.8540
17	1.8339	3.2531	.9157	.5915	1.6906	.8676
18	2.0879	3.4780	.9249	.6425	1.5565	.8900
19	2.3597	3.7155	.9345	.6994	1.4298	.9112
20	2.6026	3.9672	.9463	.7617	1.3128	.9323
21	3.1801	4.2499	.9588	.8360	1.1962	.9534
22	3.9624	4.5202	.9698	.9144	1.0936	.9715
23	4.4704	4.6328	.9769	.9416	1.0620	.9793
24	5.1308	4.7307	.9852	.9660	1.0352	.9872
25	5.7534	4.7801	.9901	.9777	1.0228	.9916
26	6.3957	4.8109	.9933	.9849	1.0154	.9943
* 27	6.8807	4.8335	.9959	.9898	1.0103	.9965
** 28	8.1382	4.8755	1.0000	1.0000	1.0000	1.0000
29	9.1745	4.9174	1.0000	1.0143	.9859	1.0015

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 10H055 CONICAL EQUILIBRIUM TEMPERATURE PROBE

STA	=	1.702E+00		ME	=	6.787E+00	DEL	= 8.164E+00 CM
PO	=	1.013E+05	N/M2	DE	=	1.136E-02 KG/M3	DSTR	= 2.442E+00 CM
TO	=	4.210E+02	DEG.K	TE	=	7.540E+01 DEG.K	TH	= 4.049E-01 CM
PSW	=	2.432E+02	N/M2	UE	=	8.333E+02 M/S	THF	= 7.353E-01 CM
TW	=	2.990E+02	DEG.K	RE	=	1.842E+06 1/M	THH	= 3.520E-01 CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.7102	.2522	3.9651	0.0000
2	.0305	.3857	--	--	--	--
3	.0356	.4298	--	--	--	--
4	.0834	.6922	.7483	.2630	3.8026	.2820
5	.1067	.8581	.7579	.2711	3.6886	.3443
6	.1321	.9908	.7702	.2782	3.5945	.3924
7	.1600	1.1155	.7828	.2857	3.4999	.4359
8	.1981	1.2748	.7964	.2960	3.3559	.4878
9	.2540	1.4299	.8087	.3120	3.2047	.5347
10	.6096	1.8124	.8235	.3604	2.7749	.6307
11	.7747	1.9743	.8277	.3850	2.5971	.6646
12	1.0312	2.1632	.8340	.4158	2.4052	.7008
13	2.0650	2.9168	.8675	.5577	1.7929	.8159
14	2.3114	3.1012	.8753	.5982	1.6716	.8376
15	2.5603	3.2818	.8834	.6395	1.5638	.8573
16	3.1801	3.6907	.9018	.7391	1.3520	.8964
17	3.8379	4.0565	.9187	.8365	1.1954	.9265
18	4.4628	4.3010	.9331	.9021	1.1086	.9459
19	5.1384	4.5007	.9493	.9530	1.0493	.9631
20	5.7302	4.6035	.9608	.9765	1.0241	.9731
21	6.2662	4.6595	.9700	.9865	1.0137	.9800
22	6.9164	4.7085	.9804	.9927	1.0073	.9872
23	7.5108	4.7327	.9888	.9925	1.0075	.9923
* 24	8.1636	4.7660	.9946	.9982	1.0018	.9965
** 25	9.0449	4.7871	1.0000	1.0000	1.0000	1.0000

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108055 COMBINED TEMPERATURE-PRESSURE PROBE

STA	= 1.702E+00		ME	= 4.787E+00		DEL	= 8.164E+00 CM
PO	= 1.013E+05	N/M2	DE	= 1.136E-02	KG/M3	DSTR	= 2.442E+00 CM
TO	= 4.211E+02	DEG.K	TE	= 7.542E+01	DEG.K	TH	= 4.014E-01 CM
PSW	= 2.432E+02	N/M2	UE	= 8.334E+02	M/S	THE	= 7.275E-01 CM
TW	= 2.992E+02	DEG.K	RE	= 1.841E+06	1/M	THH	= 3.462E-01 CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.7106	.2520	3.9676	0.0000
2	.0305	.3857	.7420	.2486	4.0233	.1616
3	.0356	.4298	.7446	.2494	4.0091	.1798
4	.0838	.6921	.7652	.2565	3.8988	.2855
5	.1067	.8581	.7758	.2649	3.7757	.3483
6	.1321	.9908	.7847	.2731	3.6622	.3961
7	.1600	1.1155	.7902	.2831	3.5328	.4380
8	.1981	1.2748	.7994	.2969	3.3686	.4888
9	.2540	1.4299	.8055	.3133	3.1922	.5337
10	.6096	1.8124	.8181	.3627	2.7569	.6286
11	.7747	1.9743	.8226	.3874	2.5811	.6626
12	1.8312	2.1632	.8289	.4183	2.3905	.6987
13	2.0650	2.9168	.8635	.5604	1.7845	.8139
14	2.3114	3.1012	.8727	.6000	1.6667	.8363
15	2.5603	3.2819	.8811	.6412	1.5596	.8562
16	3.1801	3.6907	.9002	.7409	1.3497	.8957
17	3.8379	4.0565	.9178	.8366	1.1953	.9264
18	4.4428	4.3009	.9341	.9011	1.1098	.9465
19	5.1384	4.5007	.9518	.9505	1.0521	.9643
20	5.7302	4.6035	.9638	.9735	1.0273	.9747
21	6.2662	4.6595	.9739	.9824	1.0179	.9820
22	6.9164	4.7086	.9839	.9892	1.0109	.9889
23	7.5108	4.7328	.9904	.9909	1.0092	.9932
* 24	8.1636	4.7659	.9965	.9962	1.0038	.9975
** 25	9.0449	4.7872	1.0000	1.0000	1.0000	1.0000

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108101 CONICAL EQUILIBRIUM TEMPERATURE PROBE

STA	=	2.057E+00		ME	=	4.972E+00	DEL	= 4.937E+00 CM
PO	=	1.032E+06	N/M2	DE	=	1.109E-01	KG/M3	DSTR = 2.004E+00 CM
TO	=	4.235E+02	DEG.K	TF	=	7.126E+01	DEG.K	TH = 2.407E-01 CM
PSW	=	2.245E+03	N/M2	UE	=	8.413E+02	M/S	THE = 4.784E-01 CM
TW	=	3.034E+02	DEG.K	RE	=	1.931E+07	1/M	THH = 1.725E-01 CM

N	Y(CM)	M	TT/TTF	D/DE	T/TE	U/UE
1	0.0000	0.0000	.7184	.2348	4.2583	0.0000
2	.0305	1.0964	--	--	--	--
3	.0406	1.2163	--	--	--	--
4	.0546	1.3625	--	--	--	--
5	.0838	1.4978	.8109	.3006	3.3269	.5695
6	.1270	1.5946	.8184	.3101	3.2246	.5754
7	.1676	1.6645	.8232	.3176	3.1483	.5798
8	.2210	1.7323	.8274	.3254	3.0733	.5840
9	.2972	1.8041	.8339	.3375	2.9631	.5900
10	.4343	1.9927	.8446	.3574	2.7981	.6004
11	.7595	2.2946	.8634	.4001	2.4995	.7297
12	1.0643	2.5646	.8819	.4417	2.2639	.7741
13	1.4326	2.9078	.9038	.5009	1.9962	.8263
14	1.8263	3.2794	.9245	.5734	1.7439	.8710
15	2.1946	3.6063	.9395	.6449	1.5507	.9032
16	2.6264	3.9977	.9538	.7402	1.3510	.9346
17	3.2055	4.3842	.9631	.8232	1.2148	.9551
18	3.8583	4.5562	.9712	.8918	1.1213	.9700
19	4.4018	4.6961	.9785	.9303	1.0749	.9793
20	5.1283	4.8098	.9847	.9613	1.0402	.9867
21	5.7531	4.8638	.9897	.9782	1.0265	.9911
* 22	6.9367	4.9146	.9962	.9947	1.0155	.9961
23	7.6832	4.9471	.9979	.9939	1.0062	.9981
24	8.2017	4.9538	.9991	.9969	1.0051	.9989
** 25	8.9433	4.9719	1.0000	1.0000	1.0000	1.0000

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108101 COMBINED TEMPERATURE-PRESSURE PROBE

STA	=	2.057E+00	ME	=	4.972E+00	DEL	=	6.937E+00 CM
PO	=	1.032E+06 N/M2	DE	=	1.107E-01 KG/M3	DSTR	=	2.002E+00 CM
TO	=	4.243E+02 DEG.K	TE	=	7.139E+01 DEG.K	TH	=	2.623E-01 CM
PSW	=	2.246E+03 N/M2	UE	=	5.421E+02 M/S	THE	=	4.809E-01 CM
TW	=	3.042E+02 DEG.K	RE	=	1.925E+07 1/M	THH	=	1.754E-01 CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.7170	.2347	4.2614	0.0000
2	.0305	1.0964	.8002	.2608	3.8344	.4318
3	.0406	1.2163	.8074	.2700	3.7034	.4708
4	.0584	1.3625	.8129	.2838	3.5232	.5144
5	.0838	1.4978	.8167	.2984	3.3510	.5515
6	.1270	1.5945	.8205	.3093	3.2328	.5767
7	.1676	1.6645	.8256	.3167	3.1577	.5949
8	.2210	1.7323	.8318	.3237	3.0897	.6125
9	.2972	1.8340	.8384	.3357	2.9790	.6367
10	.4343	1.9927	.8475	.3562	2.8076	.6716
11	.7595	2.2946	.8633	.4001	2.4992	.7296
12	1.0643	2.5645	.8770	.4442	2.2513	.7739
13	1.4326	2.9077	.8964	.5051	1.9799	.8229
14	1.8263	3.2794	.9141	.5799	1.7244	.8662
15	2.1946	3.6062	.9298	.6516	1.5348	.8986
16	2.6264	3.9976	.9482	.7446	1.3431	.9318
17	3.2055	4.3081	.9612	.8248	1.2125	.9541
18	3.8583	4.5542	.9715	.8915	1.1217	.9701
19	4.4018	4.6960	.9798	.9290	1.0764	.9799
20	5.1283	4.8097	.9879	.9582	1.0436	.9883
21	5.7531	4.8637	.9925	.9715	1.0293	.9925
* 22	6.9367	4.9145	.9965	.9844	1.0158	.9963
23	7.6632	4.9470	.9986	.9931	1.0069	.9985
24	8.2017	4.9537	.9967	.9972	1.0028	.9977
** 25	8.9433	4.9718	1.0000	1.0000	1.0000	1.0000

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108102 CONICAL EQUILIBRIUM TEMPERATURE PROBE

STA	= 2.057E+00		ME	= 4.464E+00		DFL	= 7.036E+00 CM
PO	= 5.171E+05	N/M2	DE	= 5.508E-02	KG/M3	DSTR	= 2.142E+00 CM
TO	= 4.220E+02	DEG.K	TE	= 7.363E+01	DEG.K	TH	= 3.026E-01 CM
PSW	= 1.156E+03	N/M2	UE	= 8.366E+02	M/S	THF	= 5.507E-01 CM
TW	= 3.020E+02	DEG.K	RE	= 9.202E+04	1/M	THH	= 2.175E-01 CM

N	Y(CM)	M	TT/TTF	D/DE	T/TE	U/UE
1	0.0000	0.0000	.7158	.2438	4.1021	0.0000
2	.0305	.8353	--	--	--	--
3	.0457	1.0475	--	--	--	--
4	.0584	1.1700	--	--	--	--
5	.0838	1.3494	.7965	.2988	3.3465	.5075
6	.1092	1.4368	.8095	.3048	3.2809	.5358
7	.1346	1.5026	.8138	.3112	3.2130	.5538
8	.1880	1.5818	.8150	.3212	3.1130	.5738
9	.2311	1.6372	.8140	.3284	3.0447	.5873
10	.2946	1.7079	.8190	.3374	2.9642	.6046
11	.4423	1.8705	.8292	.3577	2.7957	.6430
12	.6756	2.0552	.8382	.3840	2.6039	.6819
13	.9093	2.2450	.8519	.4113	2.4315	.7198
14	1.2014	2.4776	.8673	.4482	2.2312	.7609
15	1.4602	2.6754	.8803	.4819	2.0749	.7924
16	1.7043	2.9051	.8934	.5249	1.9050	.8244
17	1.9634	3.1270	.9052	.5697	1.7553	.8514
18	2.2631	3.3720	.9196	.6214	1.6093	.8795
19	2.5324	3.6034	.9285	.6759	1.4795	.9012
20	3.1959	4.0709	.9453	.7944	1.2557	.9379
21	3.8633	4.3783	.9578	.8808	1.1355	.9593
22	4.3561	4.5284	.9667	.9287	1.0861	.9703
23	5.1257	4.6803	.9778	.9602	1.0415	.9820
24	5.6515	4.7548	.9855	.9776	1.0229	.9887
25	6.3681	4.8129	.9921	.9906	1.0095	.9942
* 26	7.0358	4.8391	.9961	.9955	1.0045	.9972
27	7.6378	4.8526	.9982	.9981	1.0019	.9987
** 28	8.1915	4.8637	1.0000	1.0000	1.0000	1.0000
29	8.9256	4.8742	1.0002	1.0033	.9967	1.0005

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 100102 COMBINED TEMPERATURE-PRESSURE PROBE

STA	= 2.057E+00		ME	= 4.864E+00		DEL	= 7.036E+00 CM
PO	= 5.171E+05	N/M2	DE	= 5.521E-02	KG/M3	DSTR	= 2.144E+00 CM
TO	= 4.210E+02	DEG.K	TE	= 7.346E+01	DEG.K	TH	= 3.008E-01 CM
PSW	= 1.156E+03	N/M2	UE	= 8.357E+02	M/S	TME	= 5.477E-01 CM
TW	= 3.029E+02	DEG.K	RE	= 9.236E+06	1/M	THH	= 2.141E-01 CM

	N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
	1	0.0000	0.0000	.7195	.2425	4.1238	0.0000
	2	.0305	.8353	.7844	.2535	3.9448	.3411
	3	.0457	1.0475	.7963	.2672	3.7426	.4167
	4	.0584	1.1700	.8034	.2766	3.6147	.4573
	5	.0838	1.3494	.8112	.2934	3.4079	.5122
	6	.1092	1.4388	.8138	.3032	3.2986	.5373
	7	.1346	1.5026	.8184	.3095	3.2313	.5554
	8	.1880	1.5818	.8206	.3191	3.1338	.5757
	9	.2311	1.6372	.8236	.3254	3.0729	.5901
	10	.2946	1.7079	.8269	.3341	2.9929	.6075
	11	.4623	1.8705	.8370	.3544	2.8220	.6461
	12	.6756	2.0552	.8461	.3804	2.6286	.6851
	13	.9093	2.2450	.8568	.4089	2.4454	.7218
	14	1.2014	2.4776	.8708	.4464	2.2404	.7625
	15	1.4402	2.6754	.8802	.4820	2.0747	.7923
	16	1.7043	2.9051	.8932	.5251	1.9045	.8243
	17	1.9634	3.1270	.9015	.5720	1.7482	.8501
	18	2.2631	3.3719	.9148	.6269	1.6013	.8773
	19	2.5324	3.6034	.9238	.6793	1.4720	.8989
	20	3.1953	4.0709	.9450	.7966	1.2553	.9378
	21	3.8633	4.3783	.9589	.8796	1.1369	.9598
	22	4.3561	4.5283	.9683	.9192	1.0879	.9711
	23	5.1257	4.6803	.9799	.9582	1.0437	.9831
	24	5.6515	4.7548	.9867	.9764	1.0241	.9893
	25	6.3881	4.8129	.9930	.9897	1.0104	.9947
•	26	7.0358	4.8391	.9953	.9963	1.0037	.9968
	27	7.6378	4.8528	.9991	.9972	1.0028	.9991
••	28	8.1915	4.8638	1.0000	1.0000	1.0000	1.0000
	29	8.9256	4.8742	1.0011	1.0025	.9976	1.0009

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 104103 CONICAL EQUILIBRIUM TEMPERATURE PROBE

STA	=	2.057E+00		ME	=	4.80AE+00	UEL	= 8.30AE+00 CM
PO	=	1.013E+05	N/M2	DF	=	1.1556-02 KG/M3	DSTM	= 2.714E+00 CM
TO	=	4.187E+02	DEG.K	TE	=	7.451E+01 DEG.K	TM	= 4.395E-01 CM
PSW	=	2.42ME+02	N/M2	UE	=	8.316E+02 M/S	THE	= 7.940E-01 CM
TW	=	3.034E+02	DEG.K	RE	=	1.496E+06 1/M	THM	= 3.762E-01 CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.7264	.2456	4.0737	0.0000
2	.0305	.4107	--	--	--	--
3	.0663	.4601	--	--	--	--
4	.0711	.5956	--	--	--	--
5	.1143	.8141	.7608	.2649	3.7752	.3291
6	.1651	1.0635	.7808	.2795	3.5784	.4184
7	.2104	1.2521	.7937	.2905	3.3957	.4801
8	.3460	1.5543	.8143	.3241	3.0853	.5841
9	.5994	1.7579	.8174	.3521	2.8399	.6161
10	.8890	1.9429	.8257	.3782	2.6438	.6573
11	1.1805	2.1248	.8291	.4044	2.4485	.6918
12	1.4630	2.3129	.8382	.4344	2.2757	.7260
13	1.8136	2.5208	.8506	.4751	2.1050	.7610
14	2.1819	2.7482	.8593	.5245	1.9067	.7953
15	2.5629	2.9973	.8709	.5714	1.7500	.8250
16	3.1902	3.4314	.8849	.6710	1.4903	.8717
17	3.8532	3.8516	.9074	.7779	1.2855	.9044
18	4.3467	4.1372	.9146	.8560	1.1683	.9305
19	4.1141	4.3963	.9350	.9253	1.0807	.9505
20	4.8774	4.5766	.9533	.9844	1.0326	.9676
21	4.7044	4.7039	.9720	.9933	1.0064	.9821
22	7.7851	4.7735	.9847	1.0022	.9978	.9921
* 23	8.3058	4.7906	.9944	1.0002	.9998	.9966
** 24	8.9256	4.8060	1.0000	1.0000	1.0000	1.0000

NOL BOUNDARY LAYER CHANNEL PROFILE DATA

RUN NO. 108103 COMBINED TEMPERATURE-PRESSURE PROBE

STA	=	2.057E+00		ME	=	4.806E+00	DEL	= 8.306E+00 CM
PO	=	1.013E+05	N/M2	DE	=	1.159E-02 KG/M3	DSTR	= 2.725E+00 CM
TO	=	4.174E+02	DEG.K	TE	=	7.427E+01 DEG.K	TH	= 4.339E-01 CM
PSW	=	2.428E+02	N/M2	UE	=	8.302E+02 M/S	THE	= 7.830E-01 CM
TW	=	3.036E+02	DEG.K	RE	=	1.903E+06 1/M	THH	= 3.650E-01 CM

N	Y(CM)	M	TT/TTE	D/DE	T/TE	U/UE
1	0.0000	0.0000	.7275	.2446	4.0883	0.0000
2	.0305	.4107	.7430	.2476	4.0392	.1717
3	.0483	.4599	.7537	.2461	4.0638	.1929
4	.0711	.5953	.7656	.2489	4.0174	.2483
5	.1143	.8140	.7742	.2603	3.8414	.3320
6	.1651	1.0635	.7902	.2761	3.6216	.4211
7	.2108	1.2520	.8039	.2908	3.4393	.4831
8	.3480	1.5542	.8119	.3251	3.0763	.5672
9	.5994	1.7570	.8182	.3518	2.8428	.6164
10	.8890	1.9429	.8253	.3784	2.6426	.6572
11	1.1405	2.1247	.8282	.4089	2.4458	.6914
12	1.4630	2.3128	.8357	.4407	2.2690	.7240
13	1.8136	2.5208	.8482	.4764	2.0990	.7599
14	2.1819	2.7682	.8606	.5237	1.9096	.7959
15	2.5629	2.9972	.8708	.5715	1.7497	.8249
16	3.1902	3.4318	.8882	.6723	1.4875	.8709
17	3.8532	3.8515	.9067	.7786	1.2844	.9082
18	4.3967	4.1371	.9215	.8542	1.1707	.9314
19	5.1181	4.3942	.9383	.9220	1.0846	.9522
20	5.8776	4.5766	.9557	.9662	1.0350	.9688
21	6.7843	4.7037	.9754	.9897	1.0104	.9838
22	7.7851	4.7735	.9918	.9973	1.0027	.9946
* 23	8.3058	4.7904	.9955	.9992	1.0008	.9971
** 24	8.9256	4.8060	1.0000	1.0000	1.0000	1.0000